VSB TECHNICAL UNIVERSITY OF OSTRAVA
FACULTY OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

Multilevel solar power converters

Víceúrovňové solární výkonové měniče

Phuc Hau Nguyen

Diploma Thesis
Supervisor: Ing. Vladislav Damec, Ph.D.
Ostrava, 2021

VSB – Technical University of Ostrava
Faculty of Electrical Engineering and Computer Science
Department of Electronics

Diploma Thesis Assignment

Student: **Phuc Hau Nguyen**

Study Programme: N0714A060007 Applied Electronics

Title: Multilevel solar power converters
Víceúrovňové solární výkonové měniče

The thesis language: English

Description:

1. Analyze the electrical characteristic of a typical solar panel under different condition.
2. Create a circuit model of solar panel with solar power converter structure in numeric simulation environment and perform its optimization.
3. Simulate the multilevel / cell power solar converter configuration.
4. Compare the performance between common solar power converter structure and multilevel cell solar converter structure.

References:

1) S.Basu, S. Maiti: "A Hybrid Modular Multilevel Converter for Solar Power Integration",IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 55, NO. 5, SEPTEMBER/OCTOBER 2019
2) Infineon AG, "Benefits of multilevel topologies in power-efficient energy storage systems (ESS)", www.infineon.com/energy-storage-systems
3) W. Jiang, B. Fahimi, "Maximum Solar Power Transfer in Multi-port Power Electronic Interface",
4) A. Alexander, M. Thathan, "Modelling and analysis of modular multilevel converter for solar photovoltaic applications to improve power quality, IET Renewable Power Generation, 2015, Vol. 9, Iss. 1, pp. 78–
5) S.M. Fatemi, M. S. Shadlu, A. Talebkhah: "Comparison of Three-Point P&O and Hill Climbing Methods for Maximum Power Point Tracking in PV Systems", 2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC)

Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

Supervisor: **Ing. Vladislav Damec, Ph.D.**

Date of issue: 01.09.2020

Date of submission: 30.04.2021

doc. Ing. Petr Palacký, Ph.D.	prof. Ing. Pavel Brandštetter, CSc.
Head of Department	*Dean*

Abstract

The thesis aims to draw the main issue of the solar panel on solar system configuration and giving the solution for the issue. From the beginning, the thesis studies the characteristics of the solar panel under the varying condition as irradiance and temperature. For optimizing the performance of the non-linear characteristic, a method Perturb & Observe (P&O) based on Maximum Power Point (MPP) tracking is tested and applied with the DC/DC converter.

The commonly used solar structure converter and the multilevel converter structure have been implemented. Both configurations have a series connection between panel to panel or module to module. The analysis is divided into two cases as ideal condition and partial – shading condition. The ideal condition complied as standard test condition (STC) that the solar panel is illuminated by the irradiance of 1000W/m^2 with the temperature during test 25°C. The partial – shading is levelized for every panel. The inherent issues are shown by the characteristic of the commonly used solar converter. The current path has been affected by the series connection which leads to the low power extraction from the solar cell. The multilevel solar converter has taken the advantages against the commonly used one. The results are shown by doing the numerical simulation in the MATLAB environment.

Keyword: Photovoltaic, partial shading, MPPT (maximum power point tracking), P&O (Perturb & Observe), solar converter structure.

Práce si klade za cíl nastínit potíže při konfiguraci solárního systému a poskytnout řešení tohoto problému. Na začátku práce je provedena literární rešerše a jsou uvedeny vlastnosti solárních panelů za různých podmínek, jako je ozáření a teplota. Pro optimalizaci výkonu nelineární charakteristiky je testována metoda Pertub & Observe (P&O) založená na sledování maximálního bodu výkonu (MPP) a použita s DC / DC převodníkem.

Pro srovnání měničových struktur byla implementována běžná jednoduchá a víceúrovňová struktura měniče. Obě konfigurace pracují se sériovým řazením solárních panelů. Analýza je rozdělena na dva případy jako ideální stav a stav při částečném zastínění. Ideální stav je definován jako standardní testovací podmínka (STC), že solární panel je osvětlen 1000 W/m^2 a pracuje při teplotě 25 stupňů celsia. Částečné stínování je pro každý panel vyrovnáno. Problémy s částečným zastíněním jsou patrné z charakteristik běžného solárního měniče. Proudový odběr z panelů byl ovlivněn sériovým připojením, což vede k odběru malého výkonu ze solárního baterie. Víceúrovňový solární konvertor dosáhl většího výkonu proti běžně použitému. Výsledky jsou zobrazeny provedením numerické simulace v prostředí MATLAB.

Klíčové slovo: Fotovoltaika, částečné stínování, MPPT (sledování maximálního výkonu), P&O (Perturb & Observe), struktura solárního měniče.

ACKNOWLEDGEMENT

I would like to thank my supervisor prof. Ing. Vladislav Damec, Ph.D. for his guidance and support. Without him, it would never be possible to finish this thesis topic in this pandemic situation.

Thank you to all teachers in the VSB-Technical University of Ostrava that always try to help with patience and give knowledge to students but also to all people who work on making education and research accessible for as many as possible people.

Thank you with love to my family who gives me the opportunity and friends who help me to not get crazy when I am feeling down.

Thank you for always staying beside me.

Table of Contents

List of symbols and abbreviations used

1. Physical symbols

D	Duty cycle	-
E	Energy	J
f	Switching frequency	Hz
G	Irradiance	W/m^2
I	Current	A
I_D	Current across diode	A
I_L	Photogenerated current	A
I_O	Reverse saturate current	A
I_{PV}	Photovoltaic current	A
I_{SC}	Short circuit current	A
I_{SH}	Shunt current	A
L	Inductance	H
N	Quality factor	-
P	Power	W
P_{loss}	Power loss	W
$P_{TRUEMPP}$	True maximum power point	W
Q	Charge	C
R	Resistance	Ω
R_{DS_on}	Drain source resistance	Ω
R_{th}	Thermal resistance	K/W
R_{th_ch}	Thermal resistance case to heatsink	K/W
R_{th_ha}	Thermal resistance heatsinks to ambient	K/W
R_{th_jc}	Thermal resistance junction to case	K/W
T	Temperature	°C
T_c	Case temperature	K
T_H	Heatsink temperature	K
T_J	Junction temperature	K
V	Voltage	V
V_D	Voltage across diode	V
V_F	Forward voltage	V
V_{GS}	Gate source voltage	V
V_{OC}	Open circuit voltage	V
V_{PV}	Photovoltaic voltage	V
V_T	Thermal voltage	V
η	Efficiency	%

2. Abbreviations used

PV	Photovoltaics
MPPT	Maximum power point tracking
P&O	Perturb & Observe
PWM	Pulse width modulation
STC	Standard test condition

List of Figures

List of Tables

Introduction

The solar panel creates direct current by absorbing the energy from sunlight. Then it is converted to an alternating current to transfer to the main power grid. The solar panel has contributed to the world's clean energy source and grown significantly (Madsen & Hansen, 2019) as long as it saves electric bills for people using household electricity. It is one of the potential renewable energy in the future to supply energy for housing, space vehicles, mobility electronic devices etc. Solar panel itself is improved every day to achieve better power efficiency (NREL).

Many issues are leading to the large reduction in extracting energy from the photovoltaic cell such as partial shading, temperature, aging, manufacturing tolerance, or soiling (Doubleday, Choi, Maksimovic, Deline, & Olalla, 2016). The issue is getting serious when the solar system is connected in series or parallel. Each panel has its electrical characteristic as well as it is affected by the partial shading, temperature, …etc. In series connection, if only one or few panels are affected by the partial shading and connected with the un-shading panels, the mismatching problem occurs and could cause a huge reduction in output energy. These days, some commercial solar companies have created the power optimizer for avoiding the partial shading as Solar Edge, Solar Magic, Tigo Energy, etc.

If the system is connected in parallel, the total power is achieved maximum due to its isolating current. But the disadvantage of this configuration is the high current and the voltage stay the same which it's not the purpose of the work. Therefore, the purpose to choose a series connection is to extract maximum power and sufficient voltage to supply to the grid. Also, the current would stay in the limitation level.

The multilevel converter structure is the preferred choice for solving this problem. It's could recover more energy around 25 -35% of energy loss (Doubleday, Choi, Maksimovic, Deline, & Olalla, 2016). This structure is contained the MPP tracking technique and DC/DC converter to find the maximum power point on each electrical characteristic.

This thesis work is divided into 4 chapters to gradually explain the issue and present the configuration of the solar converter. The first part is an overview of the development and construction of the solar panel. The solar panel has been invented and improved its efficiency through many years. The second part gets acquainted with the MATLAB environment to perform the electrical characteristic of the solar panel. It analyses its limitation under different conditions as irradiation, temperature gradient, and aging.

Thanks to power electronics, solar power can be harvested much more based on the choice of the type of semiconductor components and its technique control. The third part is about designing the schematic wiring of the solar panel converter and the control of the working point MPP. The third part is about comparing the difference between the common solar panel and the multicell converter. The result will be discussed regarding output power, efficiency, and recovery energy of the converter. All the work will be proved and analyzed by several simulations in the MATLAB environment.

1. Overview of the development and construction of solar energy

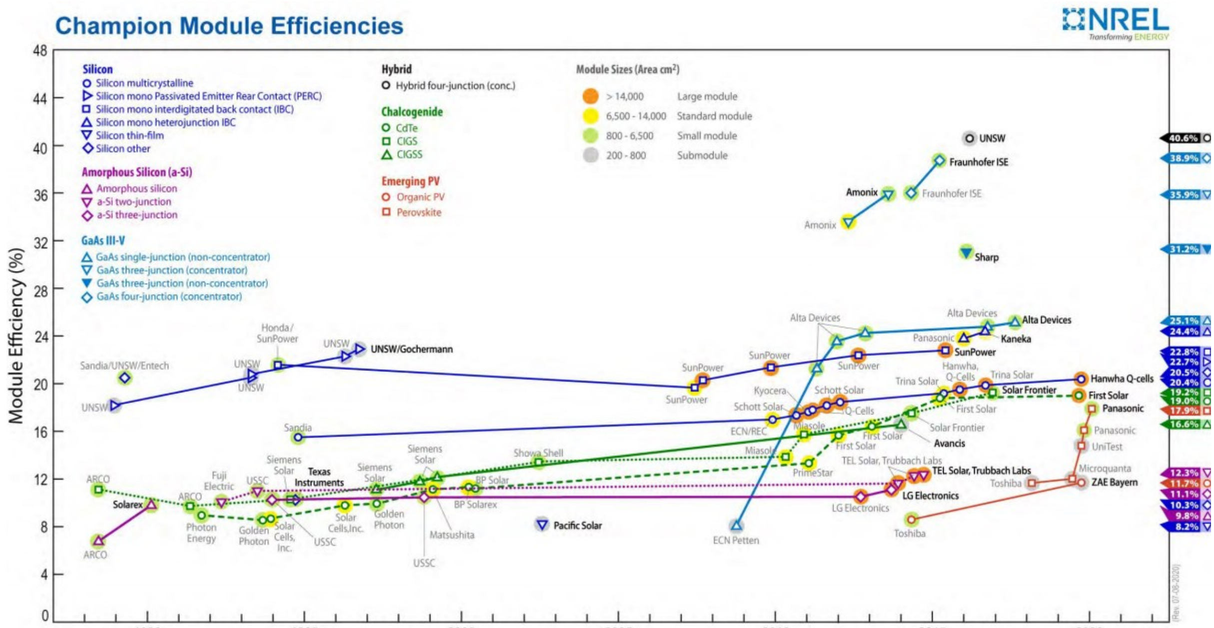


Figure 1.1 Reported timeline of champion solar module energy conversion efficiencies (NREL)

The solar cell can generate electricity in a frequency range of light. Some of the light does not belong to its range (too low frequency or too high frequency as ultraviolet, infrared, …etc) so the solar cell skips it. It cannot take 100% sunlight as we expect. Because of that, the power efficiency is limited also. Some commercial companies create a solar cell in the range from 15% to 24% efficiency with the power around 300W – 365W (NREL).

Figure 1 is the report timeline for solar module energy conversion efficiencies. This report timeline shows that at the beginning solar panel got only 8% of energy from the sun then it gradually increases to 20% in 2020. The largest efficiency solar module can be achieved is 45% in 2016. As another aspect, this timeline report shows that efficiency can be affected by many factors with different scales of modules and the solar manufacturer market changing every year.

The first generation of solar is made of crystalline silicon mainly and it is annotated on the top left of the figure with blue color. With mono silicon material, the efficiency can be raised from 15% to 24% and it can be implemented by SunPower company. The average efficiency is from 15% to 20% made of silicon multi-crystalline manufactured by Schott solar.

The common of these two companies SunPower and Schott solar is it produces large modules of more than 14,000 cm^2. The other material is amorphous silicon (a-Si) which is annotated purple color under Silicon. This type of material does not get much efficiency as Silicon. The GaAs III-V with a single junction to four junctions was created. It can achieve high efficiency from 25.1% to 38.9% but used for small module size only.

The other technique increase rapidly is emerging PV (photovoltaic) which can be a potential in the PV field. This material is an efficient light absorber, and its properties can be tuned by chemical synthesis. It can change the invisible light to appropriate light and if it stacks with many layers, it can attain higher efficiency. This technique is found that it is easier to manufacture and reduce the price compared to the silicon one. The compete of harvesting solar energy is a hard battlefield that depends on many elements as module construction, type of sunlight, etc.

1.1. Solar cell construction

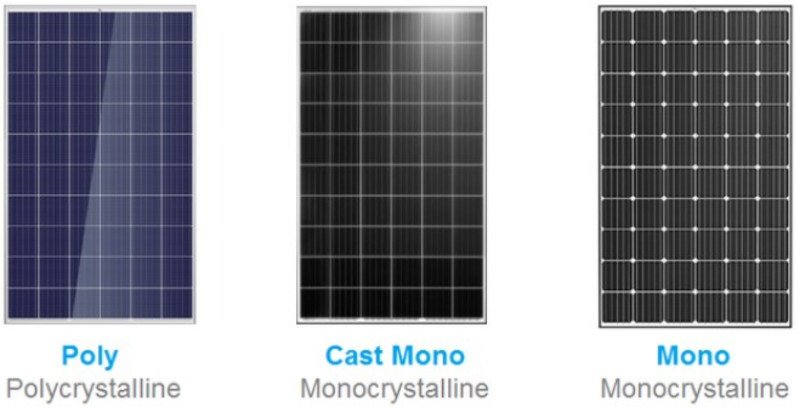


Figure 1.2 Solar panel with 72 cells (Svarc, 2020)

The solar cell is made of semiconductor material and constructed in 3 layers. The top contains silicon and a small amount of phosphorus that has more electrons than silicon. The top layer can be called negative type or n-type. The thin bottom layer contains both silicon and boron that has fewer electron than silicon which make it freer to move. The bottom layer can be called positive type or p-type. The thicker middle layer has only slightly fewer electrons which makes it p-type.

When light waves hit the top surface of a solar cell with a specific solar spectrum (350-1140nm). It can be absorbed into the middle layer of the cell. If the wavelength spectrum is too low or high, the light wave can be reflected or can not pass through the cell. The appropriate light wave hit an electron off a silicon atom, setting the electron loose and leaving an area of positive charge where the electron used to be. The loose electron moves toward the top and reaches the top n-type layer which accepts the electron. Similarly, the loose hole moves toward the bottom and reaches the bottom p-type layer which accepts the hole. This continues as long as sunlight shine on the solar cell. The electrons and the holes have been separated, connecting a wire between the top and the bottom provides a pathway for the electron to move toward the holes. The flow of electrons is electrical current.

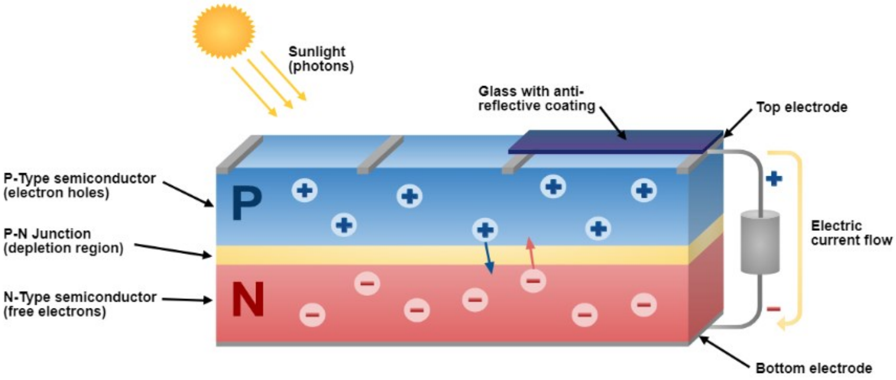


Figure 1.3 Basic PV cell structure of N type cell (Apricus)

PV cells or photovoltaic cells are made of silicon crystalline wafer. This silicon crystalline wafer can be divided into many types as polycrystalline, monocrystalline, cast monocrystalline, … etc. The highest efficiency is monocrystalline silicon cell which might bring the efficiency up to 24% but at the same time that it’s the most expensive material. The preferable one is polycrystalline silicon cell which might bring up the efficiency to 16%. Also, it has affordable price.

1.2. Solar panel construction

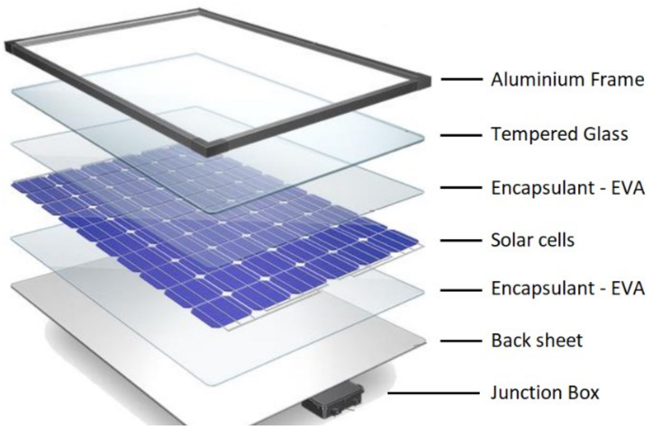


Figure 1.4 Solar panel construction (Svarc, 2020)

Solar panel contains 6 parts from the top to the bottom is an aluminium frame, tempered glass, encapsulant – EVA, solar cell, encapsulant - EVA, back sheet, and junction box.

- The aluminium frame purpose is to house all the parts of the solar panel. The frame can be made of silver or anodized aluminium alloy to keep it lightweight and to resist the high load.
- The tempered glass thickness is around 3 mm wide which has the strength to withstand a mechanical load or extreme temperature change. If the incident occurs, the glass will be broken. A short circuit current might be happening, the voltage will drop down but it’s not much threat to people. The EVA (Ethylene vinyl acetate) is a layer that it encapsulates the top and the back of the solar cell surface. This layer plays an important role to prevent moisture and dirty ingress to improve the efficiency of the solar cell.

• Back sheet: is a layer after the EVA which is made of various polymers or plastics. This layer offer protection, thermal stability, and long-term UV resistance. It has white colour.

• Junction box: is a small box place on the bottom of the panel which is important as well. This junction box has attached the cable of the solar panel. Inside the box, numerous bypass diodes prevent the current to flow backward in case the panel is shaded or dirty. The number of diodes depends on the manufacturer. If the panel has 72 cells (6 x 12) means there are 6 rows, every row has 12 cells, so the box contains 6 bypass diodes (Sunceco, n.d.).


s

Figure 1.5 Inside the junction box (Svarc, 2020)

• Connectors: solar panels are connected together by one type of plug which is called MC4 connectors. MC4 has 4mm to 6mm diameter which must be robust and can stand for high voltage up to 1000V (Svarc, 2020).

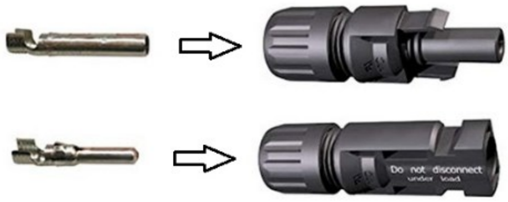


Figure 1.6 Solar MC4 connector (Svarc, 2020)

1.3. Applications

One typical solar panel contains 72 pieces connected in series and can generate 44.71 V. An array of solar panel connecting series to create desired DC voltage and current for the system is called "Solar array". But to supply energy to consumers, the photovoltaic system needs to include a booster converter, inverter, battery, charge controller, tracking system, …etc. There are many ways how solar is installed and supplied.

1.3.1. Solar farm in Viet Nam

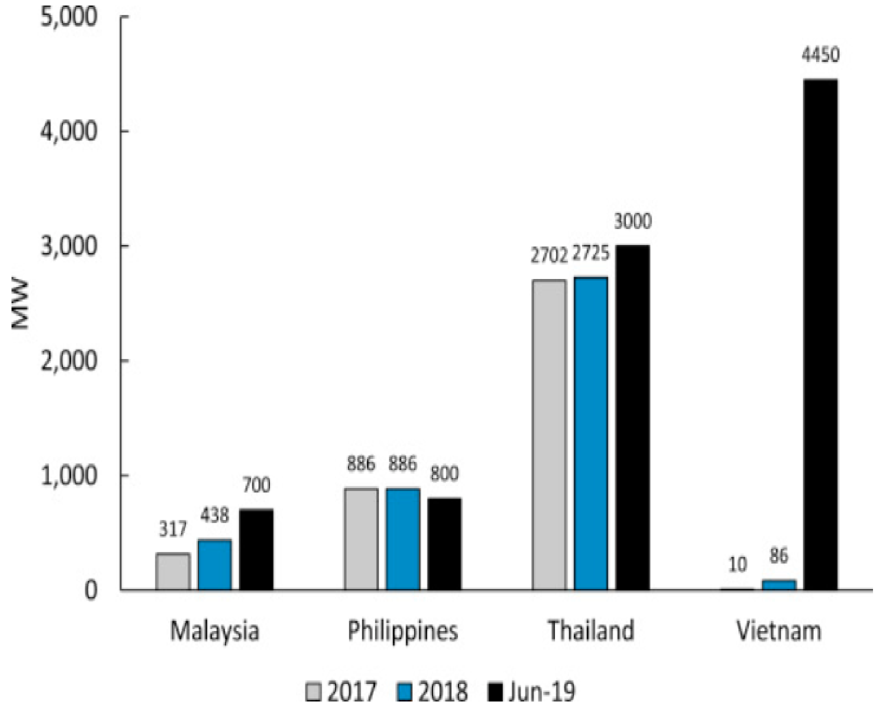


Figure 1.7 The electric generated by solar energy between Asian country from 2017-2019 (Do, Burke, Baldwin, & Nguyen, 2020)

From figure 1.7, it can be seen that Vietnam is the country that has the biggest leading photovoltaic diffusion to 4450MW (Do, Burke, Baldwin, & Nguyen, 2020) compared to the other country in 2019 and itself to the previous year of VietNam. One of the biggest solar farms in Vietnam is Dau Tieng photovoltaic which has a 500-hectare area, located 100km from Ho Chi Minh city and on the south of VietNam. Because in the south there is much more sunlight and sufficient conditions to scale-up solar PV. The Dau Tieng project is the cooperation with a foreign country with support policy as tax exemption. The reason why diffusion solar power boom just in a short time is driven by many factors.

The main driving factor in Vietnam is the shortage of energy to supply the country's electricity consumption. In the south of Vietnam is the place people come for living and working so the demand for using electricity is getting higher than before. The other driven factor is ecosystem reservation. The main energy power source is coal. Forty percent of the air pollution is made by the energy industry. However, Vietnam faces a big problem with the limited transmission capacity which transmits the huge power to the grid line generated by the solar farm. The other problems could be considered are lack of technique assistants, complex procedure, policy uncertainly, ...etc. Despite it, Vietnam has taken the first step on the journey of generating solar energy.

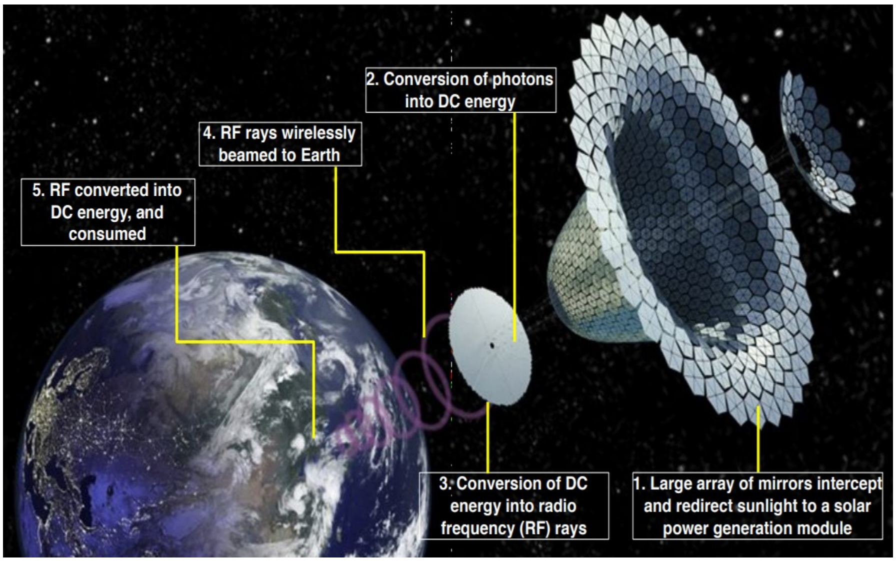


Figure 1.8 Space-based solar power (Mankins, 2014)

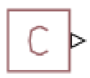
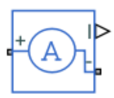
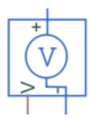
Figure 1.8 shows the space-based solar power which is a project of NASA that brings the solar panel to space because there is no atmosphere there and the sunlight can be absorbed by the panel day and night. Then transfer the power wirelessly to the world by building a large array of mirrors to intercept and redirect sunlight to a solar power generation module. This solar power generation module will convert photons into DC energy and then radio frequency rays. This radio frequency ray will beam wirelessly to the site of airport on the ground. This airport will convert them back to DC energy to consume (Mankins, 2014). The idea was created and studied for more than 75 years with the hope it brings clean energy continuously 24/7 to the world. An airplane or big vehicle can travel without a battery. However, the problem is that the prices for installation are not cheap and the equipment weight is high. There are some losses of the transmission so efficiency is not really what we want.

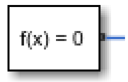
2. Performance of solar panel modelled in MATLAB

MATLAB is a software that has a wide range of possibilities to generate code, do simulations, and test in many engineering fields. There are many libraries that engineers can use to do numerical simulation. In this part, firstly, there will be a short introduction about Simscape library which has a variety of components that can be used to simulate the electrical schematic. Secondly, there will be described the equivalent circuit of the solar cells to analyze and characterize the behavior of solar under various conditions.

2.1. Short introduction in Simscape library.

The Simscape was chosen to do a simulation on the thesis work due to its support in building physical models. The table below shows a list of components used in the simulation. The description of the components and it symbol was attached also.

Component	**Description**	**Symbol**
	Foundation	
PS Constant	This block creates a physical signal constant	
Current Sensor	This block represents a current sensor. Connection + and – are electrical port which connect to the circuit. Connection I is a physical port that output current value	
Voltage Sensor	This block represents a voltage sensor. Connection + and – are electrical port which connect to the circuit. Connection V is a physical port that output current value	

Utilities library		
Solver Configuration block	This block contain parameter relevant to numerical algorithms for Simscape simulations.	
Simulink-PS Converter block	This block connects Simulink outports to Physical Signal inports	
PS-Simulink Converter block	This block connects Physical Signal outports to Simulink inports	
Electrical		
N-Chanel MOSFET	This block represents an N-channel MOSFET which included 3 port gate(G), drain (D) and source(S)	 N-Channel MOSFET
Diode	This block represents a diode	
Capacitor	This block models a capacitor with optional tolerance, operational the limit and fault modelling	
Inductor	This block models an inductor with optional tolerance, operational limits and fault modelling.	
Variable resistor	This block models a linear variable resistor. The connection + and – are electrical port.	

Electrical reference	This model contains at least one electrical reference port	
Source		
Solar cell	This block models as a solar cell combination of a current source, two exponential diodes and parallel resistor, Rp, that are connected in series with a resistance Rs	
Battery	This block models a battery which is included series internal resistance and constant voltage source	

Table 2.1 Components used in Simscape

2.2. Equivalent circuit and basic equation of solar cell

To predict the characteristic of the solar cell, this section analyzed shortly about solar cell structure with simple modelling in MATLAB/Simulink. Solar cell is modelled as a combination of current source connected parallel to one diode and shunt resistor with series resistor as shown in Figure 2.1 below.

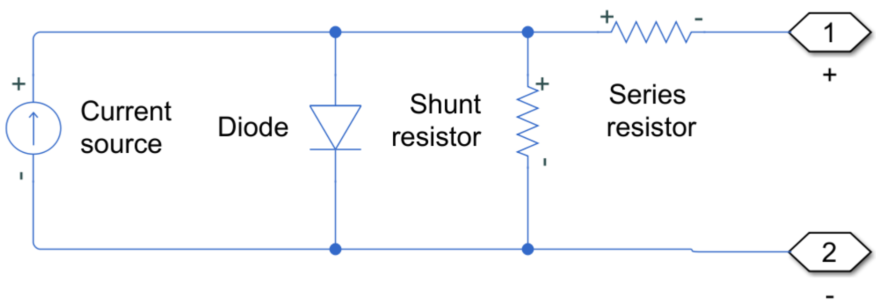


Figure 2.1 The equivalent circuit of solar cell

For generated output current, we have basis equation:

$$I = I_L - I_D - I_{SH} \,, \qquad (2.1)$$

where
I is a output current,
I_L is photogenerated current,

I_D is diode current,
I_{SH} is shunt current.

Based on Shockley diode equation, diode can give the I-V characteristic in forward and reverse bias direction:

$$I_D = I_0\left(e^{\frac{V_D}{n.V_T}} - 1\right) \tag{2.2}$$

where
I_0 is reverse saturated current,
V_D is voltage across the diode,
n is quality factor,
V_T is thermal voltage.

For calculate shunt current, we have:

$$I_{SH} = \frac{V_j}{R_{SH}} = \frac{V+I.R_S}{R_{SH}} \tag{2.3}$$

where
I_{SH} is a shunt current,
V_j is voltage across both diode and shunt resistor also equal to sum of voltage across the output terminal and voltage across the series resistor.

So, after substitution we have:

$$I = I_L - I_0\left(e^{\frac{V_D}{n.V_T}} - 1\right) - \frac{V+I.R_S}{R_{SH}} \tag{2.4}$$

However, in MATLAB Simulink – Simscape there is already created a solar cell block with similar structure as mentioned above but with 2 diodes connect parallel, so at the end we have equation:

$$I = I_L - I_{01}\left(e^{\frac{V_D}{n.V_T}} - 1\right) - I_{02}\left(e^{\frac{V_D}{n.V_T}} - 1\right) - \frac{V+I.R_S}{R_{SH}} \tag{2.5}$$

2.3. Parameters and modelling of simulated solar panel

Solar panels simulated in MATLAB will have some main parameters. Maximum power P_{max} is an optimum power harvested from a solar cell, calculated by $P_{max} = V_{max} \cdot I_{max}$. While V_{max} and I_{max} are also voltage and current at the maximum point. I_{SC} short-circuit current is a current goes through a solar cell with the voltage going through it is zero. Similarly, V_{OC} open circuit voltage is a maximum voltage go through when current is zero.

These parameters of the solar cell are extracted from the datasheet of the manufacturer for the PV 300 W – 320 W Poly-crystalline Solar Module (Sunceco, n.d.). This model has 156 × 156 mm 72 pieces.

(6×12) – 4 BUS BARS. The model included 6 rows where every row has 12 cells and 1 bypass diode. Table 2.2 below shows the parameters of a solar panel.

One important parameter which can be considered in solar panel is efficiency. Efficiency is a parameter that allows you to compare the performance of one solar panel to another. Efficiency can be computed by the ratio of the output solar panel to the input energy from the sun. With 1000 W/m^2 for a 1.75 m^2 surface area of a solar panel, we have 1750 W energy from the sun, and the output solar panel is 300W. The efficiency here can be calculated by:

$$\eta = \frac{FF \cdot P_{out}}{P_{in}} \times 100\% = \frac{300}{1750} \times 100\% \approx 17\% \,, \qquad (2.6)$$

where *FF* is a fill factor that is determined by the ratio of the actual maximum power of the solar panel to the ideal maximum of the solar panel. Usually, the factor runs around from 0.7 to 0.8. As the PV characteristic degrades over time so the efficiency and power decrease. Fill factor might be indicated to the loss so it is essential to check it periodically. From the parameter which manufacturer gave, the fill factor can be calculated:

$$FF = \frac{V_{Pmax} \cdot I_{Pmax}}{V_{OC} \cdot I_{SC}} = \frac{37.23 \cdot 8.06}{44.71 \cdot 8.947} = 0.75 \,. \qquad (2.7)$$

Parameters of a solar panel for 1000 W/m²		
Maximum Power	P_{max}	300 W
Voltage at P_{max}	V_{Pmax}	37.23 V
Current at P_{max}	I_{Pmax}	8.06 A
Open-circuit voltage	V_{OC}	44.71 V
Short-Circuit current	I_{SC}	8.947 A
Fill factor	*FF*	0.75
Efficiency	η	17 %

Table 2.2 Parameter used in modelling (Sunceco, n.d.)

Figure 2.2 shows the modelling of solar panels connects with a variety of resistances. The solar panel is exposed with the irradiation 1000 W/m², the temperature is 25°, and connect with the load resistance. If the resistance load is equal to the resistance of the solar cell, then the solar cell will work at its maximum power point. The load resistance is computed by the division of voltage to the current at the maximum power point.

In case the resistance load goes lower or higher than the optimum load, the power will be decreased. MPPT (maximum power point tracking) is a process to seek the point and keep the maximum power transfer under various conditions.

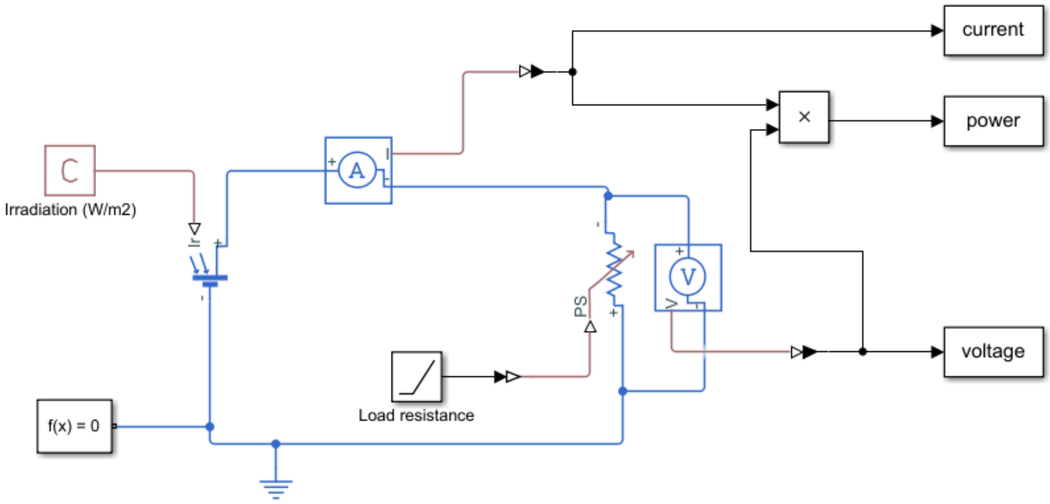


Figure 2.2 Solar panel with variety of load resistance

After applying the model on MATLAB as in Figure 2.2, the electrical characteristic for a solar cell is performed as a non-linear curve with the horizontal axis as voltage and the vertical axis as current. The electrical characteristic is shown in Figure 2.3. The short-circuit current occurs when there is no voltage going through the circuit. The current vertical axis, it is performing as a current source and goes into infinity with a constant current. This power point address on the vertical line only with the unloaded current at point P(0, I_{SC}). The open-circuit voltage occurs when there is no current going through the circuit. The voltage horizontal axis performs as a voltage source goes into the infinite current with constant voltage. This power point address is on the horizontal line only at P(V_{SC},0). The line that connects these two points creates a linear source but with a load resistance, the blue line is created as a non-linear curve as it's shown in figure 2.3. The orange line is P-V characteristic to show the actual maximum power where voltage is 37.23V.

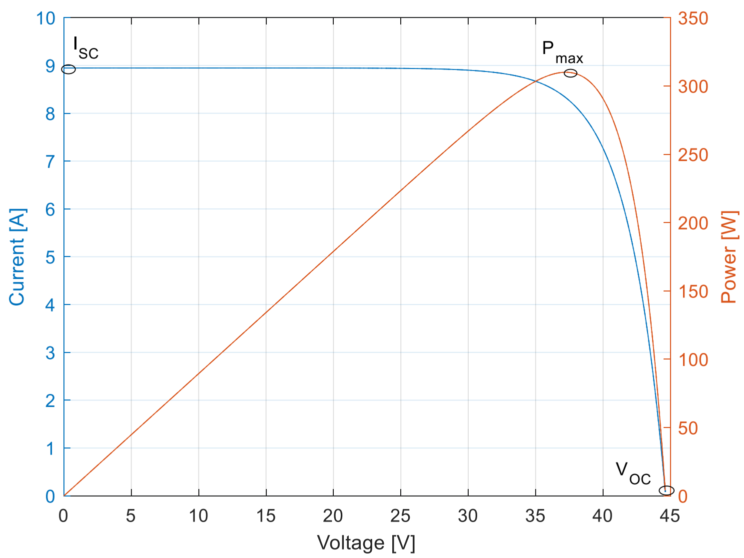


Figure 2.3 Electrical characteristic of solar panel

We apply the same parameters to the model as above with different quality factors. The range of quality factors run from 1 to 2. The quality factor describes how closely the diode's behavior matches the theoretical one. Figure 2.4 showed that the influence of the quality factor changes the maximum voltage and the maximum current of the solar cell. Due to that, it leads to decreased efficiency when the quality factor increases. It can be seen when the factor is equal to 1, it gives the optimal efficiency.

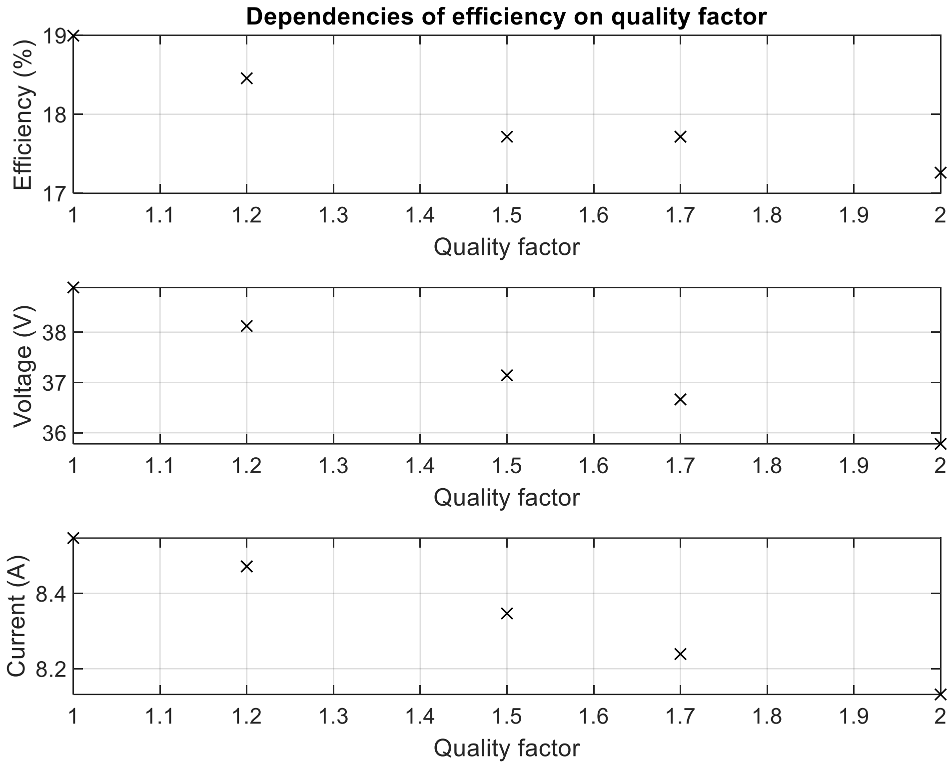


Figure 2.4 Dependencies of efficiency, voltage and current on quality factor $\eta = f(n)$

2.4. Electrical characteristics of solar module with varying irradiation at constant temperature

There are different levels of irradiance rising from 200 W/m^2 to 1000 W/m^2 performance in figure 2.5. In the datasheet of the solar panel (Sunceco, n.d.) often given maximum power point under optimum load is $P_{max} = V_{OC} \cdot I_{SC}$. This maximum power point is marked by the X point in Figure 2.5 for each characteristic. Figure 2.5 showed the P-V characteristic that the higher the solar panel is exposed to the sun or higher irradiance, the higher power could be harvested from.

With a variety of irradiance, it affects many elements as it can be seen in the I-V characteristic. Equation 2.5 mentioned above could explain partially why the non-linear current changes with a variety of irradiance. The higher the photogenerated current, the higher short-circuit current. Open circuit voltage also increases logarithmically.

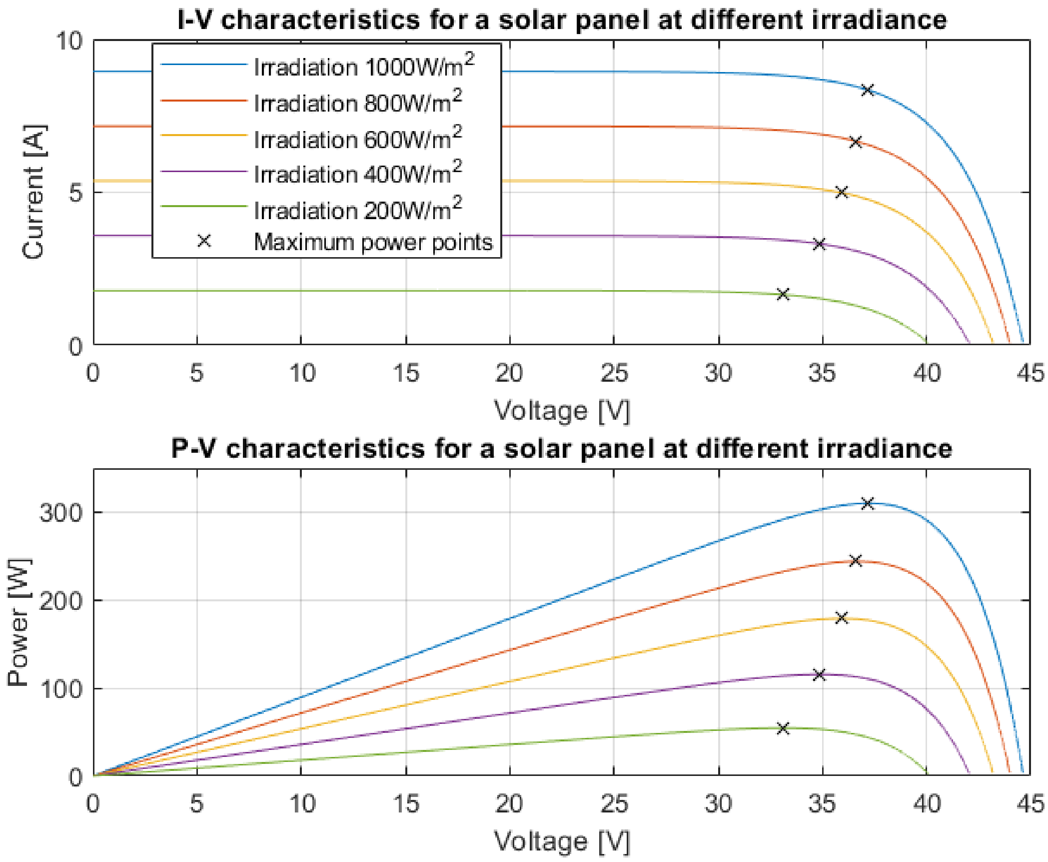


Figure 2.5 Electrical characteristic for a solar panel at different irradiance

The maximum power point is marked by the X point in the characteristic which is found by the simulation implementation. All these maximum power points, current, and voltage data with different irradiance are listed in the table below.

Irradiance (W/m^2)	200	400	600	800	1000
Current (A)	1.6	3.3	4.9	6.6	8.3
Voltage (V)	33.08	34.83	35.89	36.62	37.14
Power (W)	54.6	115.5	178.9	243.9	310

Table 2.3 Data selected from the electrical characteristic at different irradiance

2.5. Electrical characteristics of solar module with varying temperature at constant irradiation

Figure 2.6 shows that with a variety of temperature and maximum irradiance value 1000 W/m^2. The short-circuit current does not tend to change much but open-circuit voltage changes drastically. The more the temperature rises, the more open circuit voltage decreases. The solar cell has a good operating point at 10°C means that the maximum power point is addressed if the temperature is lower. Open circuit voltage has the equation:

$$V_{OC} = \frac{k \cdot T}{q} ln\left(\frac{I_L}{I_O} + 1\right), \tag{2.8}$$

where
k is Boltzmann constant,
T is absolute temperature,
q is elementary charge,
I_L is photogenerated current,
I_O is reverse saturated current.

This equation could depict the importance of the temperature change to open-short circuit voltage and reverse saturated current.

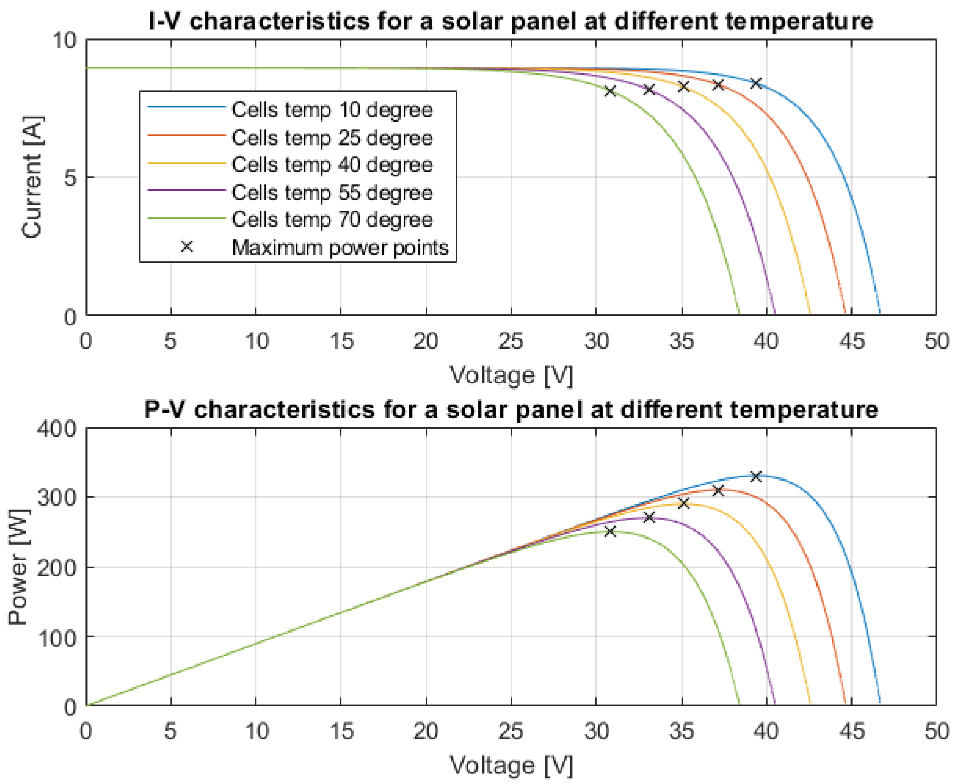


Figure 2.6 Electrical characteristics for a solar panel at different temperature

The maximum power point is marked by the X point in the characteristic which is found by the simulation implementation. All these maximum power points, the current and the voltage data with different irradiance will be listed in the table below.

Temperature (°C)	10	25	40	55	70
Current (A)	8.38	8.34	8.2	8.1	8.1
Voltage (V)	39.4	37.14	35.1	33.06	30.8
Power (W)	330.31	310.02	289.9	269.94	250.2

Table 2.4 Data selected by the electrical characteristic at different temperature

2.6. Aging of solar panels

As we discussed previously, the solar power is affected by the irradiance which is illuminated by the sun and the temperature as well. However, those are not the only factor to affect the power – voltage characteristic. The other factor should be taken into account is aging of the solar panel. The solar panel does not have stable efficiency over time. The old solar panel has lower efficiency compared to the new one. A typical poly – crystalline solar module has guaranteed 90% of output for the first 12 years and 80% of output up to 25 years (Sunceco, n.d.).

Equation 2.3 could depict the output current containing the shunt current also which regard series and shunt resistance. It leads to the impact of power and efficiency. There will be a power loss of solar cells unless perfect adjustable resistance. To achieve stable efficiency over time, the resistance should remain the same. However, the series resistance increases due to the decrease of contact resistance (Gatz, Dullweber, & Brendel, 2011) , and shunt resistance decreases due to metal migration (Dhass, Natarajan, & Ponnusamy, 2012).

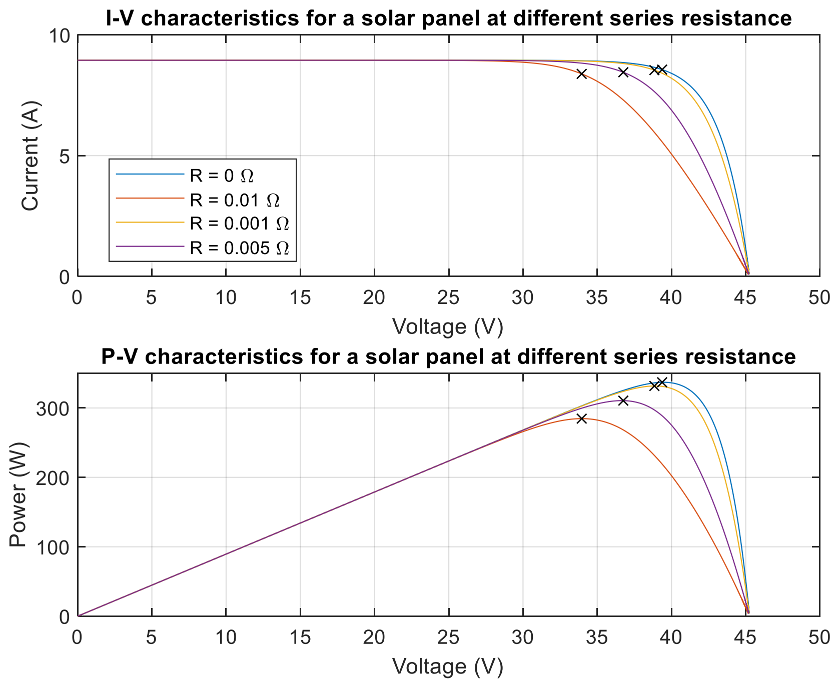


Figure 2.7 Electrical characteristic of solar panel at different series resistance

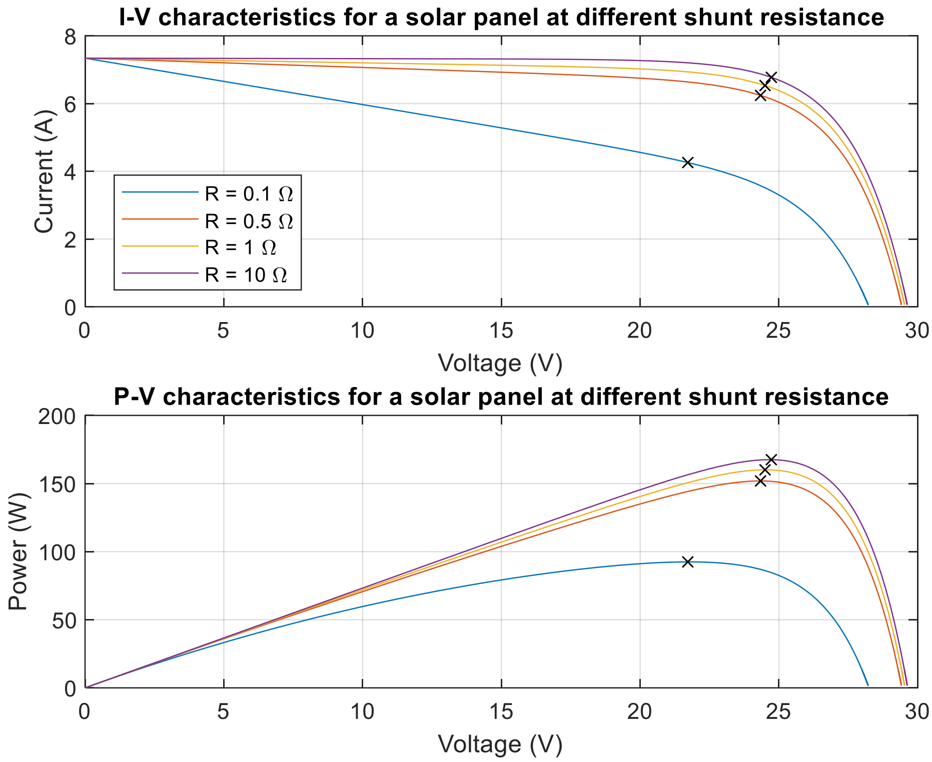


Figure 2.8 Electrical characteristic of the solar panel at different shunt resistance

Figure 2.7 is the electrical characteristic of the solar panel simulated in MATLAB at different series resistance. The “X” point is the maximum power point. It could be seen that the current I_{max} remains the same while the voltage V_{max} changes. This leads to maximum power point change in P-V characteristic. The highest power point occurs when the series resistance gets smaller and achieves the best at zero.

Figure 2.8 is the electrical characteristic of the solar panel simulated in MATLAB at different shunt resistance. The shunt resistance working reverse with the series resistance. The maximum power point achieves the best when resistance goes to infinite. The blue line is exponentially decreasing and has the smallest power point.

If there are a number of the old panels connected in series, it is found that the power loss is higher than connected in parallel (Kaushika & Rai., 2007). But if one old panel and one new panel connects in series or in case the panel has some different parameters because of its sensitivity. The mismatch issue occurs again due to different characteristics. The thesis is going to propose the solar converter structure that will solve this problem.

3. DC/DC conversion and maximum power point tracking

The goal of the work is to seek the maximum energy of solar modules. Because of that, there will be consideration about transfer efficiency and converter efficiency. This work will look at the structure of the converter which will be simulated in the solar submodule. DC-DC converter is applied to the system configuration. In the end, MPPT technique by using P&O method is introduced and implemented.

3.1. DC/DC conversion

The converter used in this thesis is a buck-boost converter which has the ability to make the output voltage greater or less than the input voltage. This converter circuit uses transistor switches, inductor, diode and capacitor to reduce ripple of voltage as it is shown in the figure 14. The MOSFET transistor was chosen as a transistor switch and it will be switched by using a PWM signal. The operation of the converter depends on the on and off stage of the switch.

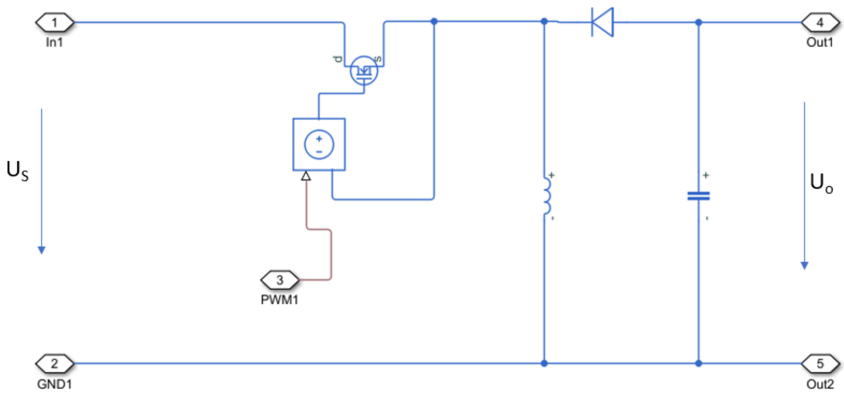


Figure 3.1 Electrical diagram of converter

The converter has two operations:

- On-stage: first operation when the switch is closed. The power source supplies energy as normal. The current go through the switch and the flow charges an inductor and inductor store some energy. The diode prevents the current to go to the right side and the capacitor use this state to provide the voltage and energy to the load.
- Off-stage: when the switch is open, the inductor creates some opposed voltage and discharges the energy. The voltage is higher so it can charge the capacitor and the load. The diode goes forward biased, creating a loop on the right side.
- The output voltage will depend on this stage which can be explained by the equation:

$$U_o = U_s \cdot \frac{-D}{1-D}, \tag{3.1}$$

Where U_o is the output voltage, U_s is the source voltage or the input voltage to the converter, D is the duty cycle.

3.2. Maximum power point tracking technique.

The idea is switching duty cycle through pulse width modulation to get the desired voltage which is controlled by the MPPT technique. It can perform maximum power point tracking under varying conditions such as irradiance and temperature, ... etc. There are several methods how to keep maximum power point such as Incremental Conductance, Factional Open-circuit voltage, Temperature method, …etc (Elgendy & Atkinson, 2013), (Ahmad, 2010). Perturb and Observe(P&O) methods will be implemented in this solar module configuration with a variety of irradiance. This method and another alternative overview and comparison can be found in (Fatemi, Shadlu, & Talebkhah, 2019).

This method adjusts the amount of voltage by power feedback. If the power increases, the adjustment will fix the direction till the power does not increase anymore. The method step by step collects the data of voltage and current from the solar module then multiplies both of them. The next step is creating the difference between the voltage at present and the previous time. Similarly, to the power, then making multiplication between different voltage and different power. If the result is positive, the duty cycle is decreased. If the result is negative, the duty cycle is increased.

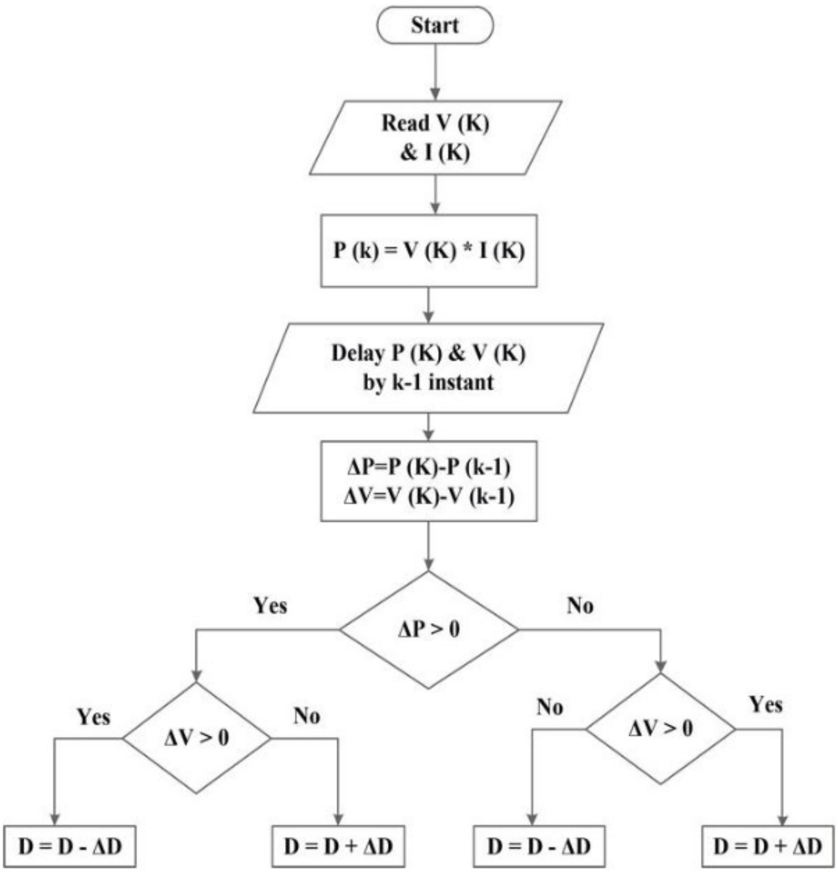


Figure 3.2 The flowchart diagram of one step P&O method.

Figure 3.3 is the system architecture of solar module connect DC/DC converter. The P&O block has the input connected directly to the voltage and current probes of solar to select the data and the output is duty cycle. This system will be tested with varying irradiance by the repeating sequential interpolated input block.

Figure 3.4 is the schematic inside the P&O block which contains unit delay block, zero-order hold, MATLAB function block, saturation block, PWM generator block and gain block in order from the left to the right. The unit delay block will sample and hold one period delay. Zero-order hold block hold all the input as a vector for the same sample period. The algorithm will be implemented in the MATLAB function block. Saturation block is limiting the signal from 0 to 1.

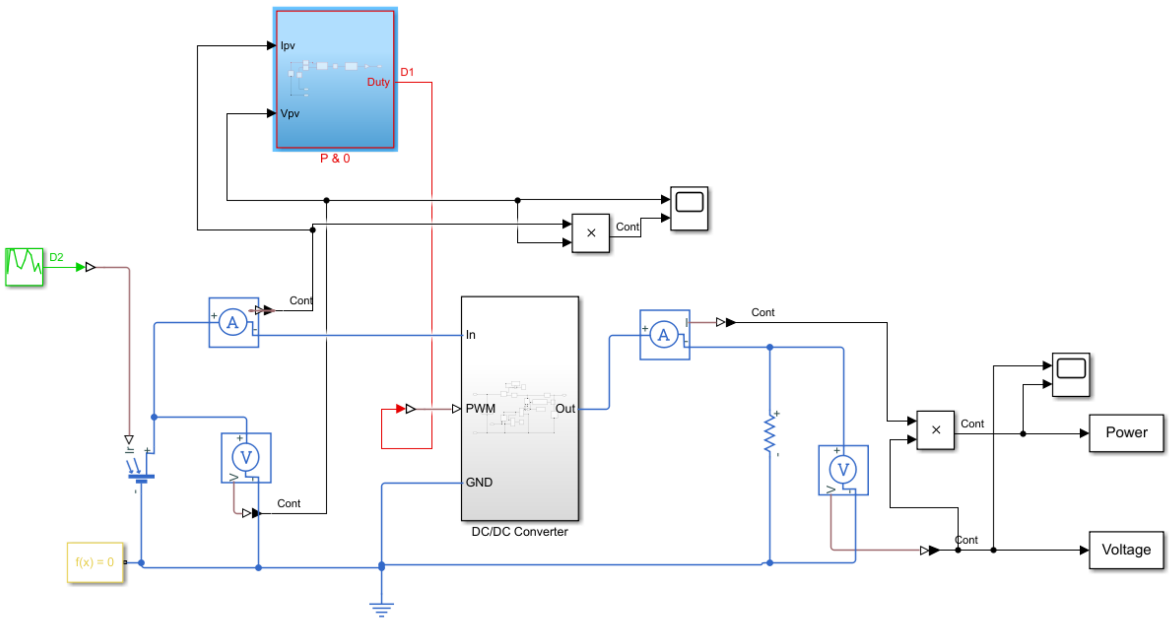


Figure 3.3 . Solar module connects with a DC/DC converter controlled by MPPT technique under varying irradiance.

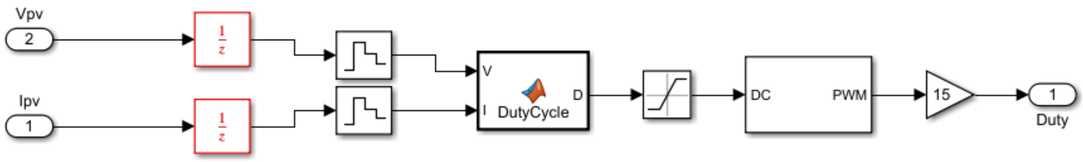


Figure 3.4. Schematic inside the P&O block

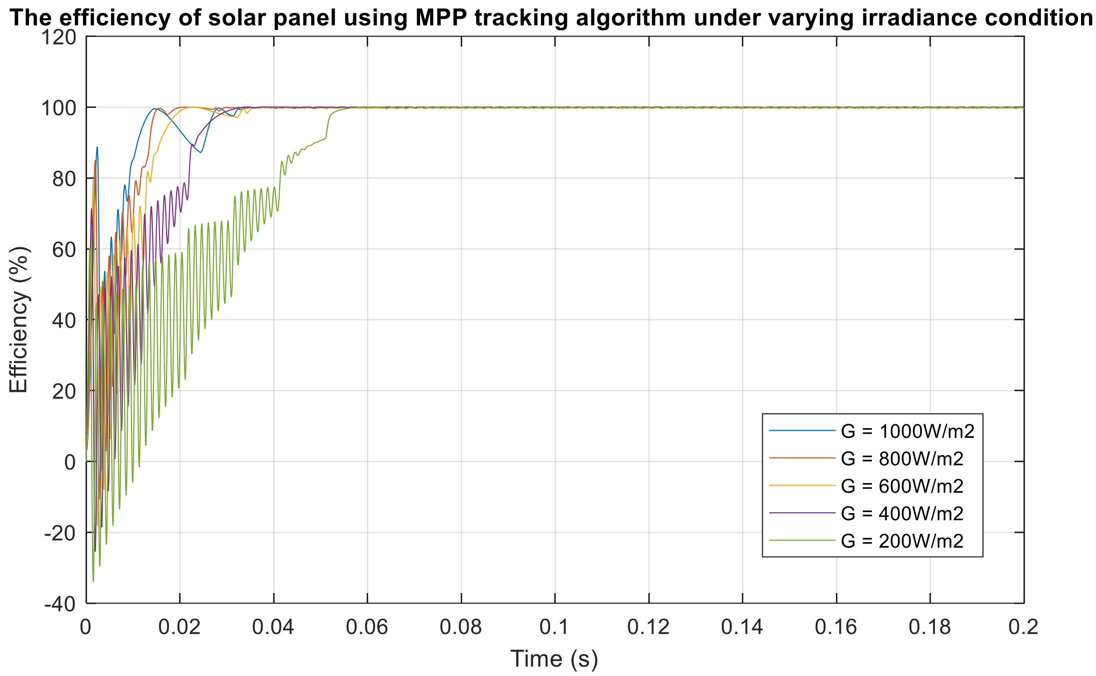


Figure 3.5. The efficiency of the MPP tracking algorithm under varying irradiance condition (range from 200W/m^2 to 1000W/m^2)

From chapter 2, there is a mention about the efficiency that can take energy from the sun to the solar cell around 17%, from 1750W to 300W. However, these efficiencies depend on chemical engineering, different kinds of chemicals will give different frequencies as it is mentioned at the beginning. The module that we sample for all the simulation is a Poly-crystalline module. Then, the objective in this chapter is to assure that the transfer efficiency is optimal. Due to some shading condition as irradiance and temperature, the efficiency will change.

In this part, the efficiency is the ratio between the true maximum power point which was collected from chapter 2, table 2.3, and the maximum power point which used the MPPT technique. This efficiency of the maximum power point tracking algorithm under varying conditions will run from 200W/m^2 to 1000 W/m^2 as it's shown in figure 3.5.

From figure 3.5 with the full irradiance, blue line, the tracking works well and fastest. It can achieve 100% in 0.01s with small oscillation in the transient state. However, the more the irradiance reduces, the longer time it takes to achieve 100% efficiency, especially with 200W/m^2, the green line. The least partial shading achieves a steady-state at 0.06s. Even it has much oscillation on the transient state.

In general, the tracking works well with 100% efficiency and is fast with all the kind of shadings condition.

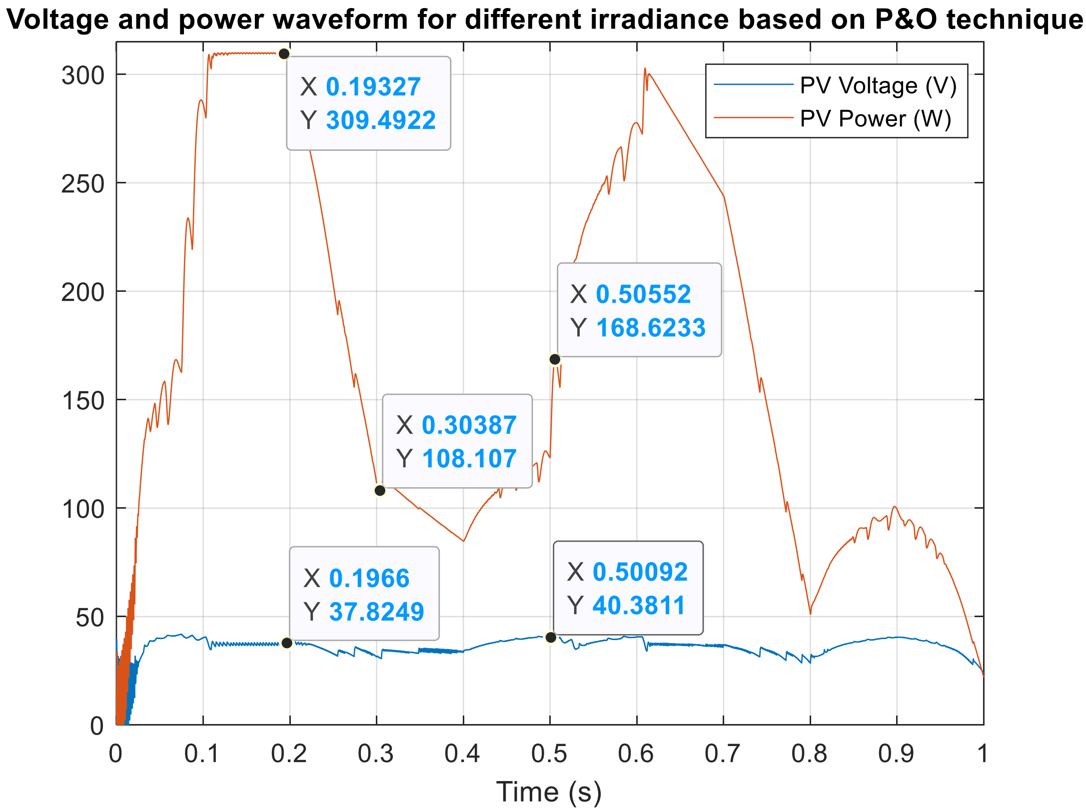


Figure 3.6. Voltage and power waveform for different irradiance with time from 0 to 1s

Time (s)	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Irradiance (W/m^2)	200	1000	1000	400	300	600
Time (s)	0.6	0.7	0.8	0.9	1	
Irradiance (W/m^2)	1000	800	200	500	100	

Table 3.1 The setting of time and irradiance

The result is shown in figure 3.6 which includes waveform of the voltage and the power performed over time. The orange line is power and the blue line is the voltage from solar cell. The table below anotate the irradiance in different time and the output between this point is interpolated. The figure shows that the implementation works perfectly and achieves the result quite fast under varying irradiance in 0.1 second which mean it's has a good resilience. At 0.1-0.2s, there are full irradiance so it's reach 310W with voltage 37.8V. At 0.5s, there is 600W/m^2, so it's reach 168W which is 95% efficiency and the voltage is 40V.

3.3. Power loss calculation

There are numerous of factors need to be taken care of to achieve the optimum harvest energy. After considering the efficiency of the maximum power point tracking above, the efficiency of the converter should be considered to perform the optimum harvest energy from the solar modules. This part will prove mathematically that the DC/DC converter has high efficiency of about 96% and less power loss.

As the information is given above, the converter will contain mainly transistor MOSFET, inductor, and diode and all of its parameters will be applied the same in MATLAB Simulink work. Some calculations will be drawn to verify the output power and efficiency of the converter.

For convenience calculation, the table of parameters of all the components is drawn up in the table below.

	Parameter of MOSFET	
U_{dd}		45 V
Q_{ds}	Drain to source charge	37 nC
U_{ds2}	Drain to source voltage 2	22.5 V
U_{ds1}	Drain to source voltage 1	45 V
$R_{ds}(on)$	Drain to source resistance	0.0169 Ω
$I_{ds}(on)$	Drain to source current	9 A
R_g	Gate resistance	2.4 Ω
U_{dr}	Drive gate voltage	15 V
U_{plateu}	Plateau voltage	5 V
U_{gs}	Gate to source voltage	5 V
F	Switching frequency	50000 Hz
D	Duty cycle	0.3
Q_{rr}	Reverse recovery charge	801 nC
	Parameter of diode and inductor	
Uto	Forward voltage of diode	0.6 V
I_f	Forward current	9 A
R_d	Resistance of diode	0.1 Ω
R_{ind}	Inductor resistance	0.02 Ω

Table 3.2 Parameter for calculating power loss

The power losses parameters can be calculated based on (Infineon Technologies, 2002)

Gate to drain 2 charge:

$$C_{gd2} = \frac{Q_{ds}}{Uds2 - Ugs} = 0.925\ (nF) \tag{3.2}$$

Gate to drain 1 charge:

$$C_{gd1} = \frac{Q_{ds}}{U_{ds1} - U_{gs}} = 2.11\ (nF) \tag{3.3}$$

Time rising 1:

$$t_{r1} = U_{dd} - R_{ds}(on).I_{ds}(on).R_g.\frac{C_{gd1}}{U_{dr} - U_{plateu}} = 9.95\ (ns) \tag{3.4}$$

Time rising 2:

$$t_{r2} = U_{dd} - R_{ds}(on).I_{ds}(on).R_g.\frac{C_{gd2}}{U_{dr} - U_{plateu}} = 22.75\ (ns) \tag{3.5}$$

Time rising:

$$tr = \frac{tr1+tr2}{2} = 16.35\ (ns) \tag{3.6}$$

Time falling 1:

$$t_{f1} = U_{dd} - R_{ds}(on).I_{ds}(on).R_g.\frac{C_{gd1}}{U_{plateu}} = 19.91\ (ns) \tag{3.7}$$

Time falling 2:

$$t_{f2} = U_{dd} - R_{ds}(on).I_{ds}(on).R_g.\frac{C_{gd2}}{U_{plateu}} = 45.51\ (ns) \tag{3.8}$$

Time falling:

$$tf = \frac{tf1+tf2}{2} = 32.7\ (ns) \tag{3.9}$$

Energy on:

$$E_{on} = U_{dd}\ .I_{ds}(on).\frac{tr+tf}{2}.Q_{rr}.U_{dd} = 45.98\ (uJ) \tag{3.10}$$

Energy off:

$$E_{off} = U_{dd}\ .I_{ds}(on).\frac{tr+tf}{2} = 9.9\ (uJ) \tag{3.11}$$

Power loss of switching MOSFET:

$$P_{sw\_Mos} = (E_{on} + E_{off}) \cdot f = 2.79\ (W) \tag{3.12}$$

Power loss of conducting MOSFET:

$$P_{con\_Mos} = I_{ds}(on)^2 \cdot R_{ds}(on) \cdot duty\_cycle = 0.4107\ (W) \tag{3.13}$$

Power loss of MOSFET:

$$P_{loss\_Mos} = P_{sw\_Mos} + P_{con\_Mos} = 3.2\ (W) \tag{3.14}$$

Power loss of diode:

$$P_{loss\_D} = (U_{to} + (I_f \cdot R_d)) \cdot I_f \cdot (1 - duty\_cycle) = 9.45\ (W) \tag{3.15}$$

Power loss of inductor:

$$P_{loss\_Ind} = I_{ds}(on)^2 \cdot R_{ind} = 1.62\ (W) \tag{3.16}$$

Power loss of converter:

$$P_{loss} = P_{loss\_Mos} + P_{loss\_ind} + P_{loss\_D} = 14.27\ (W) \tag{3.17}$$

Efficiency of converter:

$$Efficiency = \frac{V_{in} \cdot I_{in} - P_{fav}}{V_{in} \cdot I_{in}} \cdot 100\% = 95.7\ (\%) \tag{3.18}$$

3.4. Design of constructional solution in the environment AD Inventor.

In this section, there is illustrated the converter design in the environment AD Inventor. The work is to show the example of design process of the solar converter. The power dissipation has been calculated as above, there need to be an heatsink to cool down the temperature rise of the converter. Furthermore, choice of proper fusing and protection for the converter play an important role. The MPPT controller is excluded. The convertor contains the external DC input which control the duty cycle.

- Selection of suitable switching components/modules

For switching component, I chose MOFET IRF200S234 which has package TO-263 and its parameter are listed in the Table 3.2. (Infineon, 2015)

- Selection and choice of proper driver

For control the voltage to the MOSFET with 15V, I picked the UCC35706P which has 15V voltage mode, 4MHz PWM controller with 12V/8.0V UVLO, 0C to 70C 8-PDIP 0 to 70

- Design and calculation of the heat-sink

When the converter runs at maximum operating working point, the power dissipation of the MOSFET will raise up. If we do not cool it down, the efficiency of the converter will decrease. Because of this reason, we need to find the needed thermal resistance for the converter. To calculate the thermal resistance, the following parameters are listed (Infineon, 2015):

$$T_j = 175\ °\mathrm{C};\ T_{\mathrm{a}} = 25\ °\mathrm{C}; R_{\mathrm{th\_jc}} = 0.36\ (\mathrm{K} \cdot \mathrm{W}^{-}); R_{\mathrm{th\_ch}} = 0.5\ (\mathrm{K} \cdot \mathrm{W}^{-})$$

Case temperature:

$$T_c = T_j - (R_{th\_jc} \cdot P_{loss}) = 169.8° \tag{3.19}$$

Heatsink temperature:

$$T_h = T_c - (R_{th\_ch} \cdot P_{loss}) = 162.72° \tag{3.20}$$

Heatsink to ambient thermal resistance:

$$R_{th\_ha} = (T_h - T_a)/P_{loss} = 9.64\ (\mathrm{K.W}^{-}) \tag{3.21}$$

- Design and choice of proper fusing and protection

With smaller installations for solar power, the short circuit current to be expected is lower so any protection becomes reasonable only when the number of parallel strings is at least four. The solar converter contains fusing which I created in Inventor valid only if there are at least four strings connected parallel, above 4 solar panels. The solar panel has 8.947A short circuit current. According to IEC 60364-7-712 2017 712.433.1.101.2, I chose fuse greater than 1.5 - 2.4 times the string short circuit which means fuse range can be 13.45A to 21.47A

- A brief description of the designed converter
  Input voltage: 5-37V
  Input current: 0A-10A
  Output voltage: 5V-47V
  Output current: 0A-10A
  Working temperature: -55~+175
  Working frequency: 50kHz
  Transfer efficiency: 96%

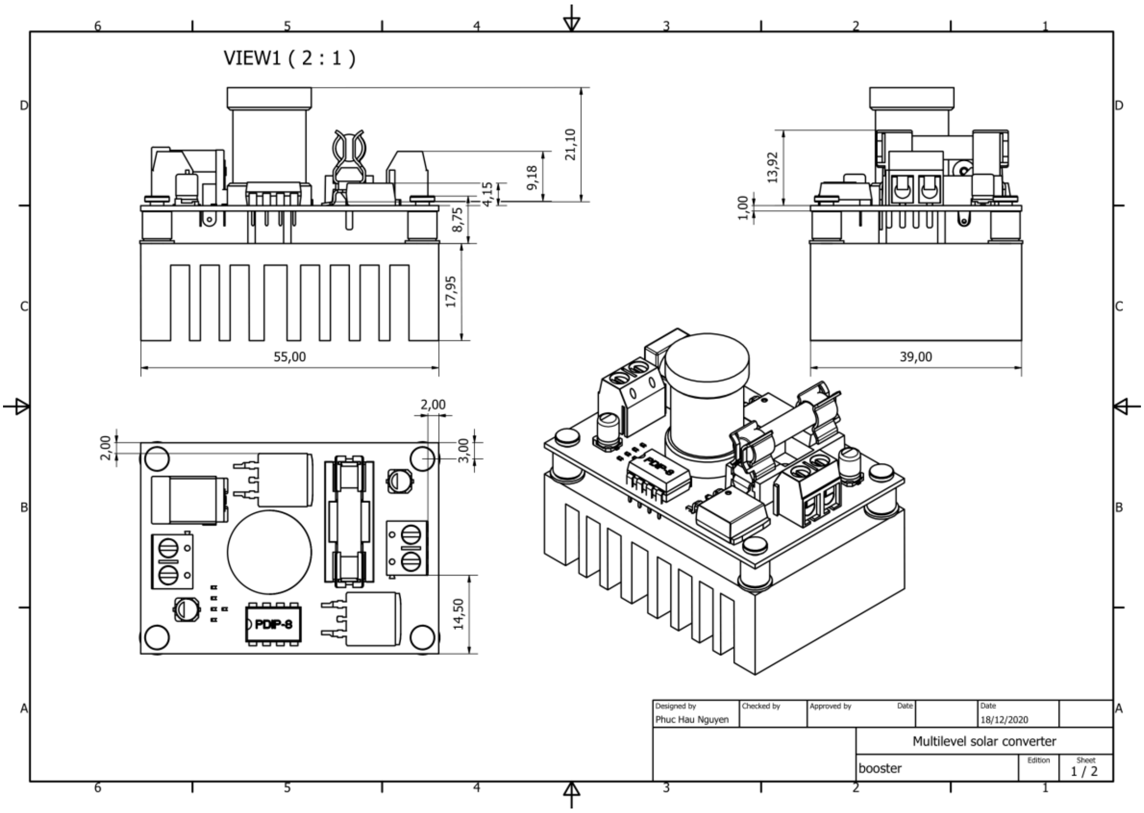
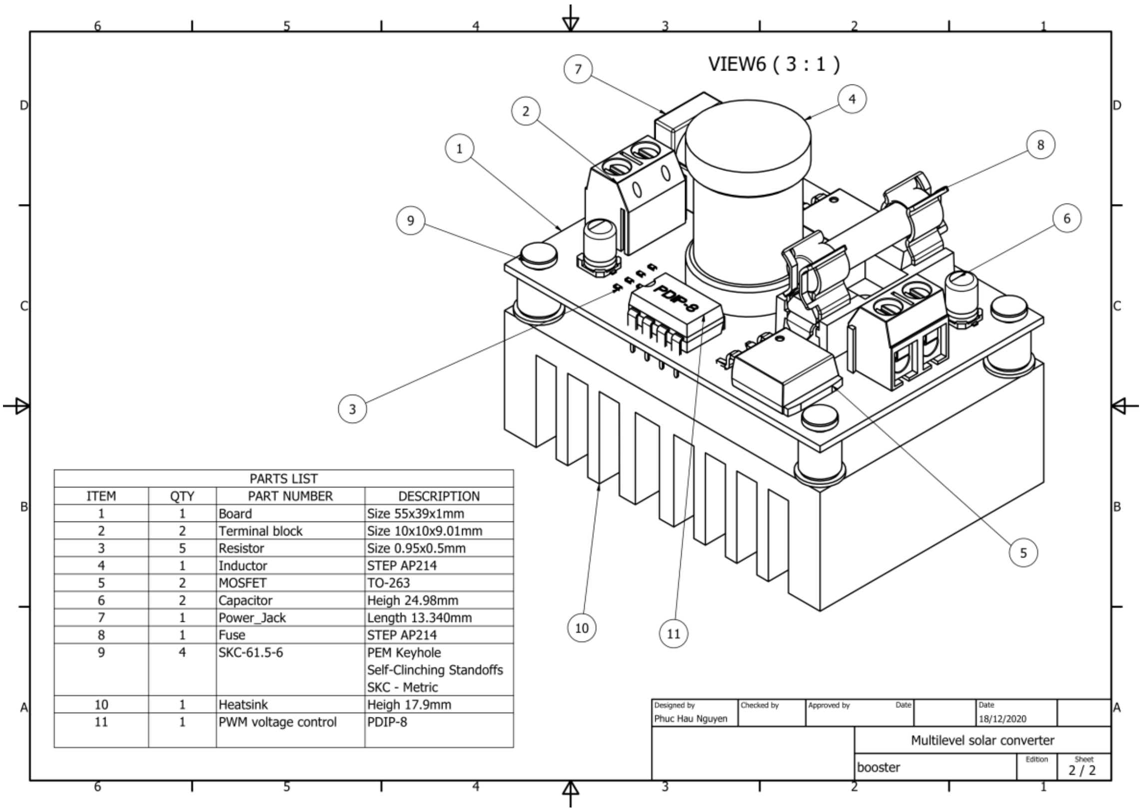


Figure 3.7 Drawing of converter with different position and dimension

Figure 3.7 is the drawing of the converter with different previews as top, on the right side, on the left side and overall look of it.



PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Board	Size 55x39x1mm
2	2	Terminal block	Size 10x10x9.01mm
3	5	Resistor	Size 0.95x0.5mm
4	1	Inductor	STEP AP214
5	2	MOSFET	TO-263
6	2	Capacitor	Heigh 24.98mm
7	1	Power_Jack	Length 13.340mm
8	1	Fuse	STEP AP214
9	4	SKC-61.5-6	PEM Keyhole Self-Clinching Standoffs SKC - Metric
10	1	Heatsink	Heigh 17.9mm
11	1	PWM voltage control	PDIP-8

Figure 3.8 Drawing of converter with part list

Figure 3.8 shows the part list of the converter drawing contain item, quantity, part number and description of the item.

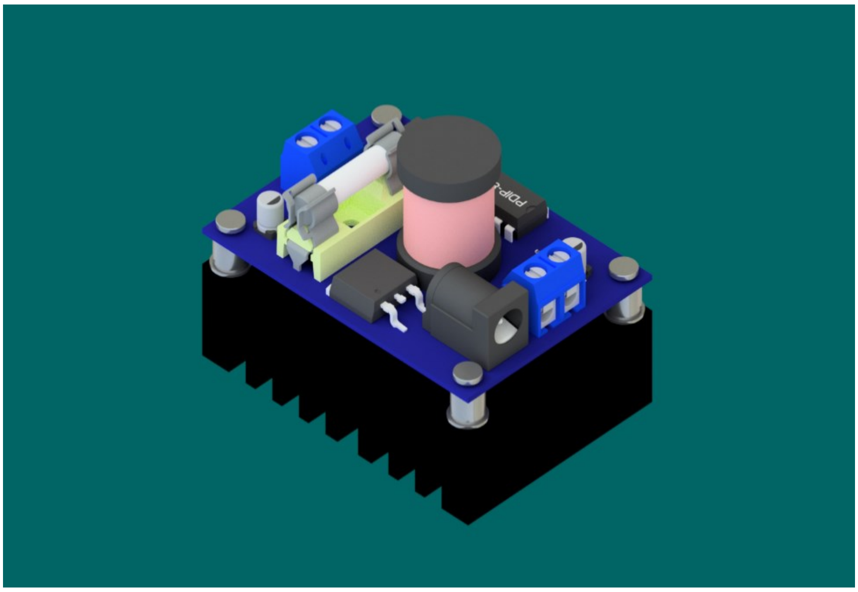


Figure 3.9. Complete picture of solar converter

Figure 3.9 Complete picture of the converter which has been taken in the Inventor.

4. The solar converter structure.

This chapter, there will be analysis and focus on how to improve the power and efficiency of the solar modules from the partial shading solar panel. The issue is mentioned in some articles (R.Ramaprabha & Dr.B.L.Mathur, 2009). On a cloudy day, a shadow of the tree or bird or some object laying on the surface of the panel will create total shading or partial shading and it's leading to loss of the power harvest from the whole solar array in case of series connection. Therefore, the goal of this chapter is to show the inherently problem of the solar panels. In the first section, we are going to propose a specific simulation setup.

Firstly, the commonly used solar converter structure has implemented and performed its characteristic. And, to prove that the diode drives the current from unshaded panel to shaded panel (Winston, Kumar, Christabel, Chamkha, & Ravishankar Sathyamurthy, 2018). After performing the situation, the chapter will optimize the solution by applying some converter structure with MPPT techniques. The difference between two structures commonly used solar converter and multilevel solar converter structure is the location of the converter with MPPT technique. The consequence will be analyzed and discussed in selected numerical simulations.

4.1. Commonly used solar converter.

4.1.1. Effect of bypass diode.

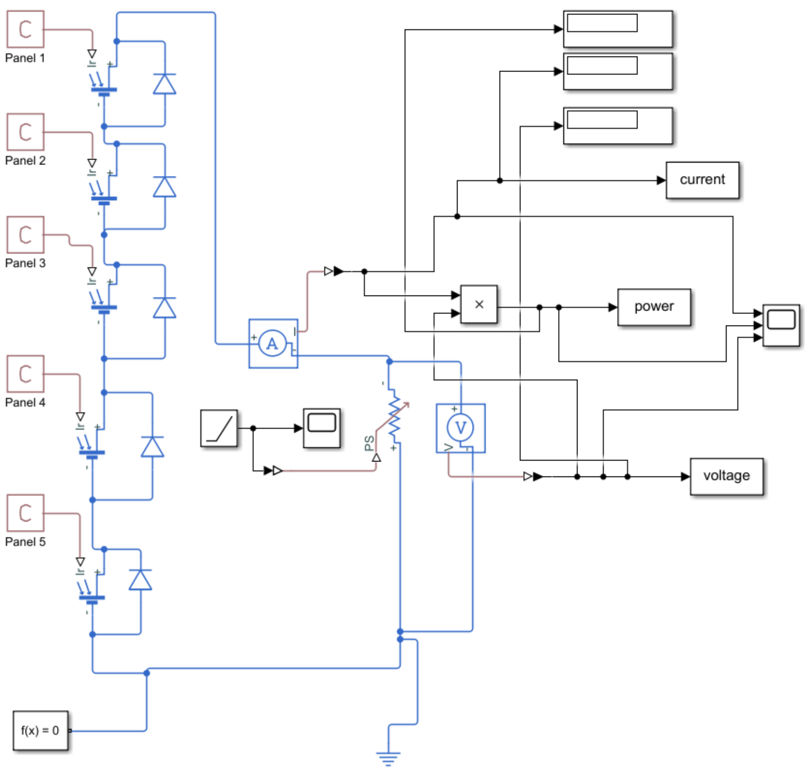


Figure 4.1. Proposed simulation model of five differently shaded solar panels

For testing the effect of the bypass diode, the simulation connection in figure 4.1 is proposed with five solar modules connecting series string which have the same parameters given in chapter 2 and temperature T = 25°. The section is divided into 3 cases.

- The first case is shaded condition include different irradiance on each panels G1 = 200W/m^2, G2 = 400W/m^2, G3 = 600 W/m^2, G4 = 800 W/m^2, G5 = 1000 W/m^2.
- The second case is shaded as the first case but the configure change with connecting parallel to bypass diode.
- The third case is no shading condition meant all the panels will be illuminated by full irradiance.

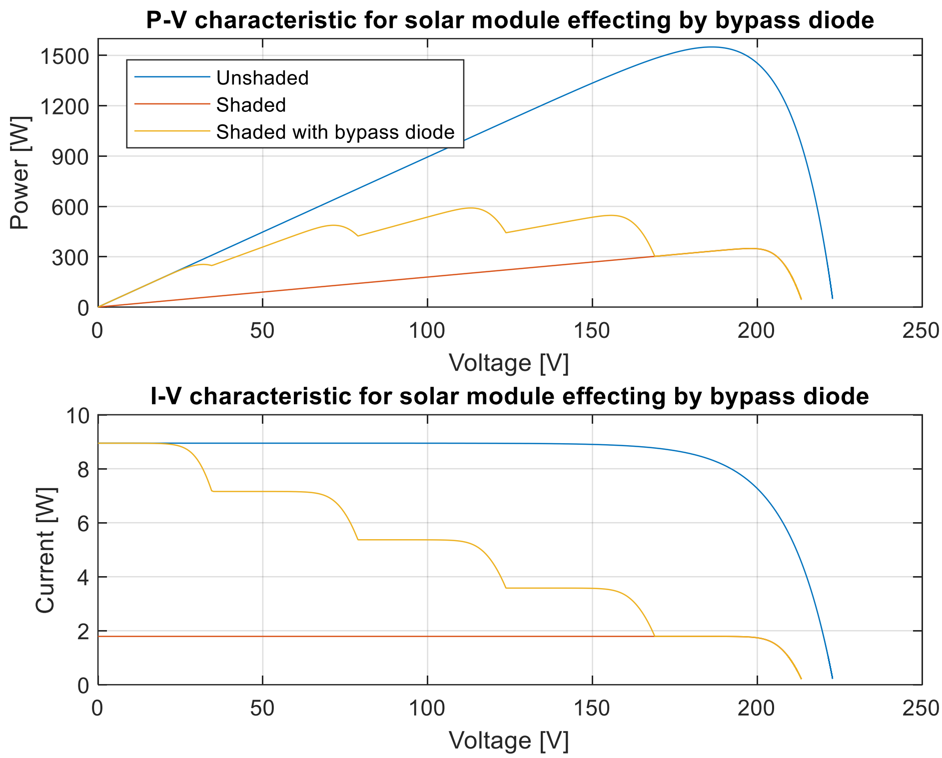


Figure 4.2. Characteristic of the whole series solar panels string affected by bypass diode

Figure 4.2 shows the P-V and I-V characteristics of solar modules' purpose to show the difference between with and without bypass diodes in case of partial shading. There will be five solar panels connected series so the open-circuit voltage will be 225 V and the short circuit current is 9A. Blue characteristic shows the “unshaded” mode means that 2 solar modules have full irradiance with 1000W/m^2. With the full irradiance, the maximum harvested power is more than 1500W, and the 185V maximum voltage shown by the “X” point marked on P-V characteristic. The I-V characteristic shows the maximum current of 9A.

Orange characteristic is “shaded” which means that there will be different irradiance on each panel: G_1 = 200W/m^2, G_2 = 400W/m^2, G_3 = 600 W/m^2, G_4 = 800 W/m^2, G_5 = 1000 W/m^2. The maximum power in the P-V characteristic reduces 5 times drastically compared with the blue characteristic which is around 310W. The maximum current reduces to 2A.

Yellow characteristic is "shaded with bypass diode" which means that the connection of the module is the same as the orange characteristic above but the difference is there will be a diode connected parallel with each panel. In this case, the shaded modules are in the short circuit stage and do not operate as a generator but as a load. Because of that, the current from the unshaded module can go through this module and save the maximum power from it as the I-V characteristic in figure 4.2 shown. Different irradiance illuminated on solar panels creates many peaks of power. The currents start from 9A and gradually reduce to current respectively with the irradiance level. The maximum power point which we can harvest from this is around 600W which is higher than the structure in orange characteristic. These days, this structure is utilized directly in the solar array. The solar module described in chapter 2 has 72 cells, dozens of cells will have 1 bypass diode which will save a lot of power if there is partial shading.

4.1.2. Behaviour of the solar string under ideal irradiance condition

For this section, the configuration contains five solar panels connected in series and has attached with one DC/DC converter has PWM controlled by P&O method based on MPPT. For the ideal condition, fives solar panels are exposed with full irradiance of G =1000W/m^2 and temperature T = 25°C following the STC. Each of them has one bypass diode. The converter is controlled by duty cycle to get the maximum power point.

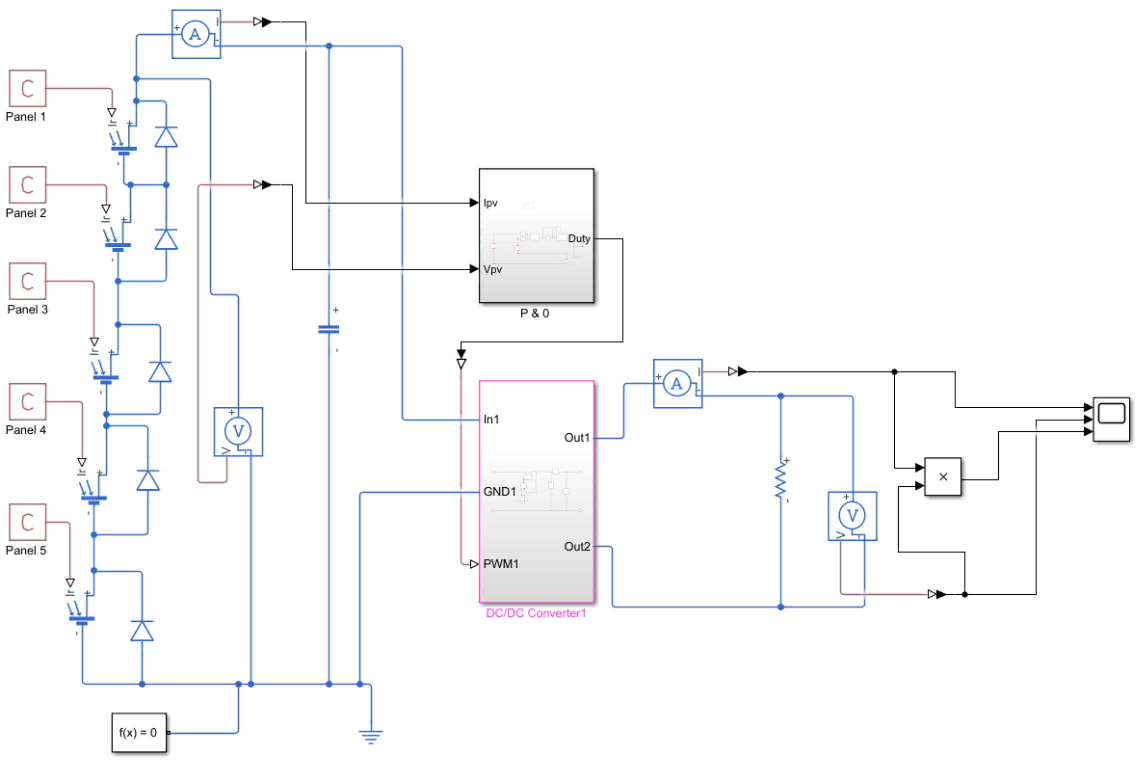


Figure 4.3. Five solar panels connect in series with a power converter with MPP tracking.

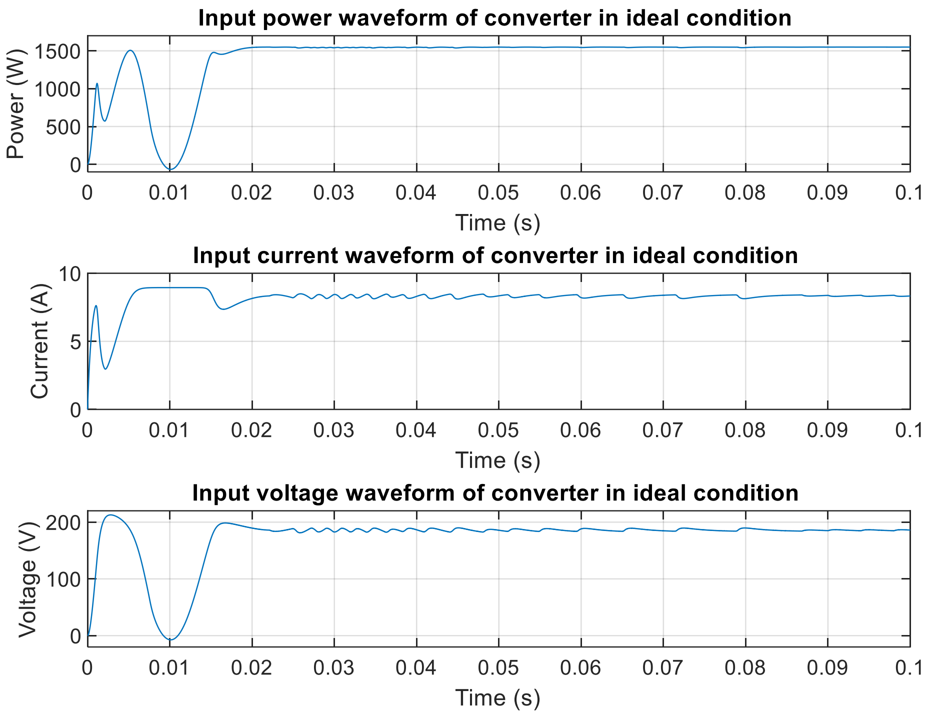


Figure 4.4. Input power energy of the converter which is harvested from five solar panels with full of irradiation G = 1000W/m^2

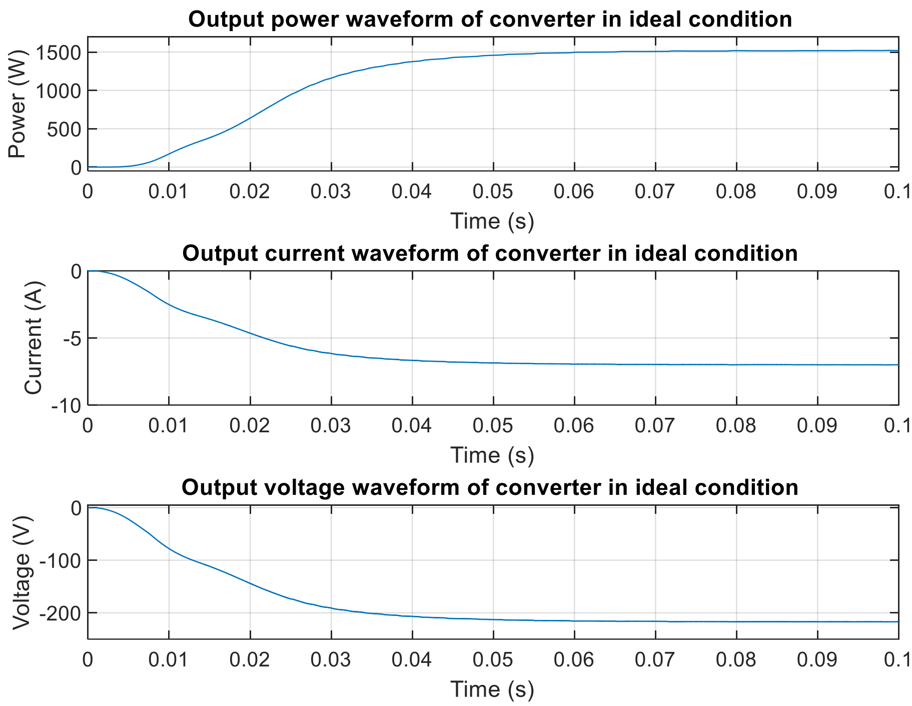


Figure 4.5. Output power energy of the converter which is harvested from five solar panel with full of irradiation G = 1000W/m^2

After applying the model and run, the maximum power harvested from both modules is 1500W. The efficiency for the power conversion is 98%, highly effective. Assuming the input maximum current from the beginning is I_{PMAX} = 8.06A and maximum input voltage from a photovoltaic cell is V_{PMAX} 37.5·5 = 187.5V. After converting, the voltage rose up from 187.5V to 225V and the current went down from 8A to -7A.

4.1.3. Behaviour of the solar string under partial shading irradiance condition

For this section, the same configuration as above is applied. The solar modules are connected in series with the bypass diode connected parallel. Each module has different irradiance as G_1 = 200W/m², G_2 = 400W/m², G_3 = 600 W/m², G_4 = 800 W/m², G_5 = 1000 W/m² and has attached with one converter and temperature is T = 25°C. The converter is controlled by duty cycle to get the maximum power point.

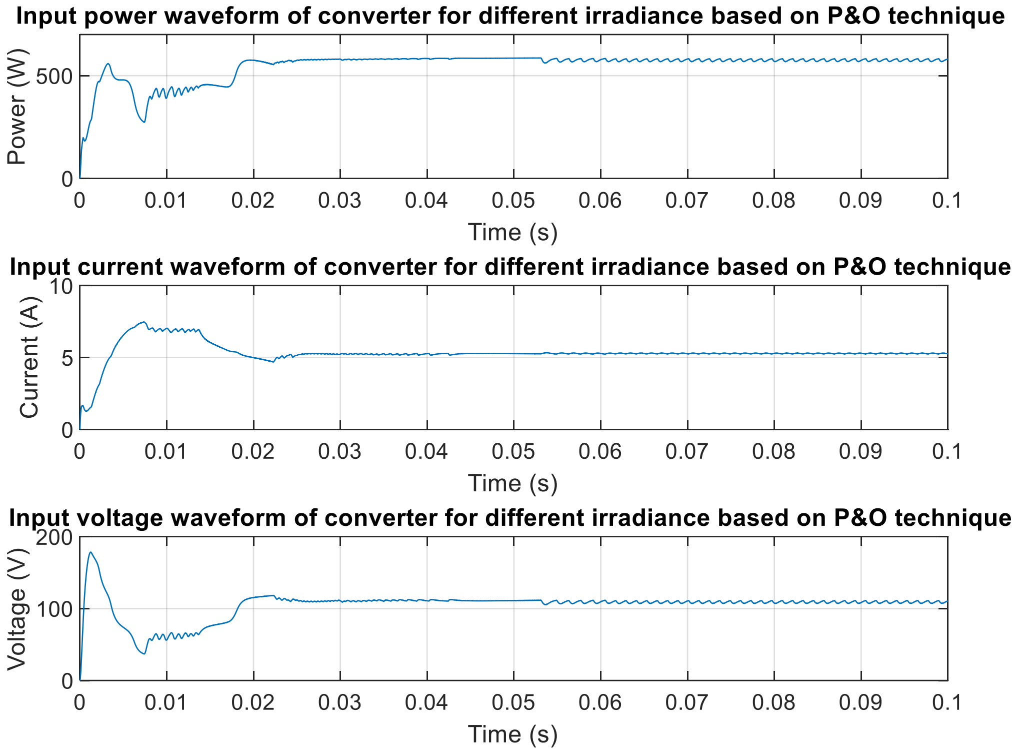


Figure 4.6. Input power energy harvested from five solar panel with different irradiation (G1 = 200W/m², G2 = 400W/m², G3 = 600 W/m², G4 = 800 W/m², G5 = 1000 W/m²)

Modules		1	2	3	4	5	Total
Irradiance (W/m²)		200	400	600	800	1000	3000
PV	Current I_{PV} (A)	5.2	5.2	5.2	5.2	5.2	5.2
	Voltage V_{PV} (V)	-1.7	-1.15	32.7	40.7	42.7	113.25
	Power P_{PV} (W)	-9	-6	170	212	222	589

Table 4.1 Data selected from the simulation at different irradiance

Figure 4.6 shows the input waveforms of the converter for different irradiance by time from 0 to 0.1s. The maximum power point is tracked and found in 0.02s. The current fluctuates from maximum current I_{PV} = 8A to 5A while the voltage rises up very fast up to 185V then drops down to 40V and gradually increases to 112V.

Table 4.1 shows the input current, input voltage, and input power extracted from each photovoltaic panel. The current stays the same but the power loss in some panels had heavy shading as 200W/m^2 up to 400W/m^2. The location of the DC/DC converter in this structure could explain the reason why the solar panel consumes power. With each panel, there will be different electrical characteristics depending on the illumination of the sun. Due to it, with many panels connected in series, the converter found it difficult to seek the maximum power point for all the panels connected in series.

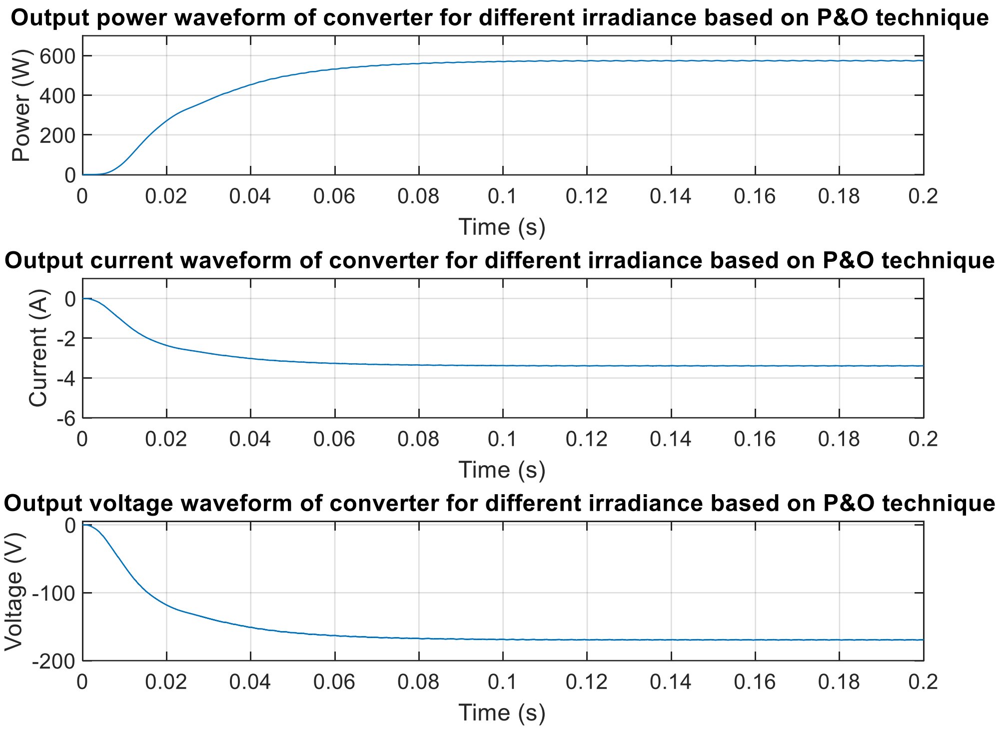


Figure 4.7. Output power energy harvested from five solar panel with different irradiation (G_1 = 200W/m^2, G_2 = 400W/m^2, G_3 = 600 W/m^2, G_4 = 800 W/m^2, G_5 = 1000 W/m^2)

Figure 4.7 is the output energy harvested from five solar panels with different irradiation. The output current and output voltage waveform after the converter is performed by time from 0 to 0.2s. After the converter, the current and voltage have reverse polarity. The current decreases from 5.2A as mentioned in the table above to -3.4A. The voltage decrease from 113V to -170V. The input PV signal gets a steady-state till 0.02s but it's taken till 0.1s for the converter to produce the output signal.

4.2. Multilevel solar converter structure

4.2.1. Behaviour of the multilevel solar converter structure under ideal irradiance condition

In this section, the architecture of the system contains five modules connected in a series string with a total maximum power of 1500W. Each module contains one panel connected with one DC/DC converter and MPP tracking. Each of them produces 300W in case assuming the solar module is exposed with full irradiance and temperature 25°C. Figure 4.8 illustrates the solar system as it was described.

If solar panel is illuminated irradiance G = 1000W/m^2 , the maximum input voltage of solar is V_{PMAX} = 37.23V. To ensure the high transfer efficiency from 300W input power, the input current requires 310/37.23 = 8.32A. The input voltage to the converter is controlled by duty cycle , in this circuit, the system requires 225V due to 5 module connnect in series string , total module provides 1500W so input current to the inverter is 1500W/225V = 6.67A. Because of that, current goes through each module have to be 6.67A. For the change of the input current, the output voltage of converter is provided 310/6.67 = 44.9V. Thanks to the converter, the input voltage increasing from 37V to 44.9V and the current decrease from 8.32A to 6.67A. The converter maintains 98% conversion efficiency in this case.

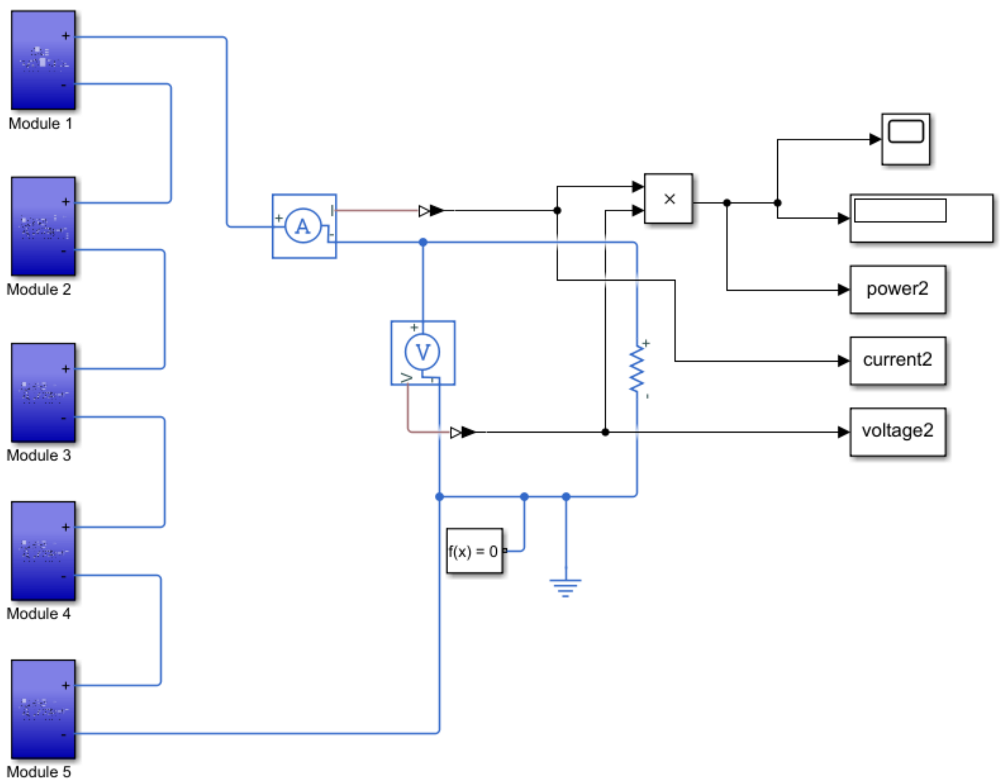


Figure 4.8. Multi solar converter configuration

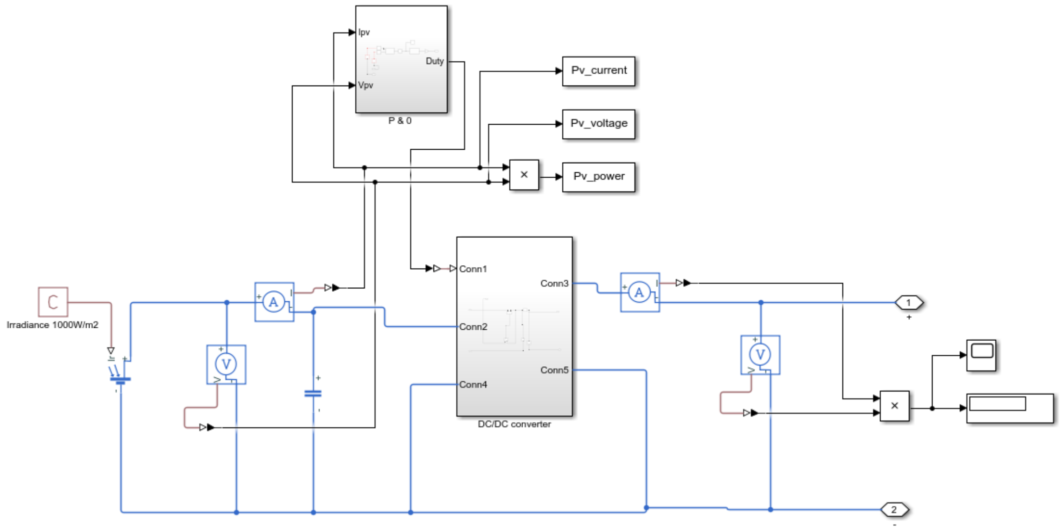


Figure 4.9. Structure of each solar module

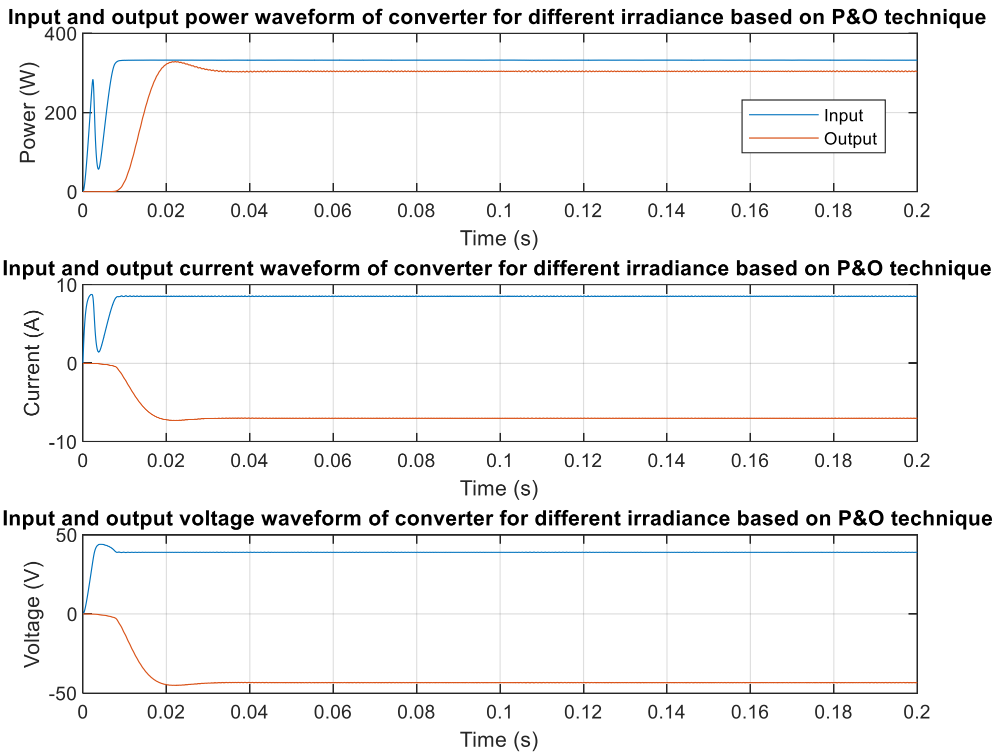


Figure 4.10. Input and output energy waveform of converter for one module with G = 1000 W/m^2

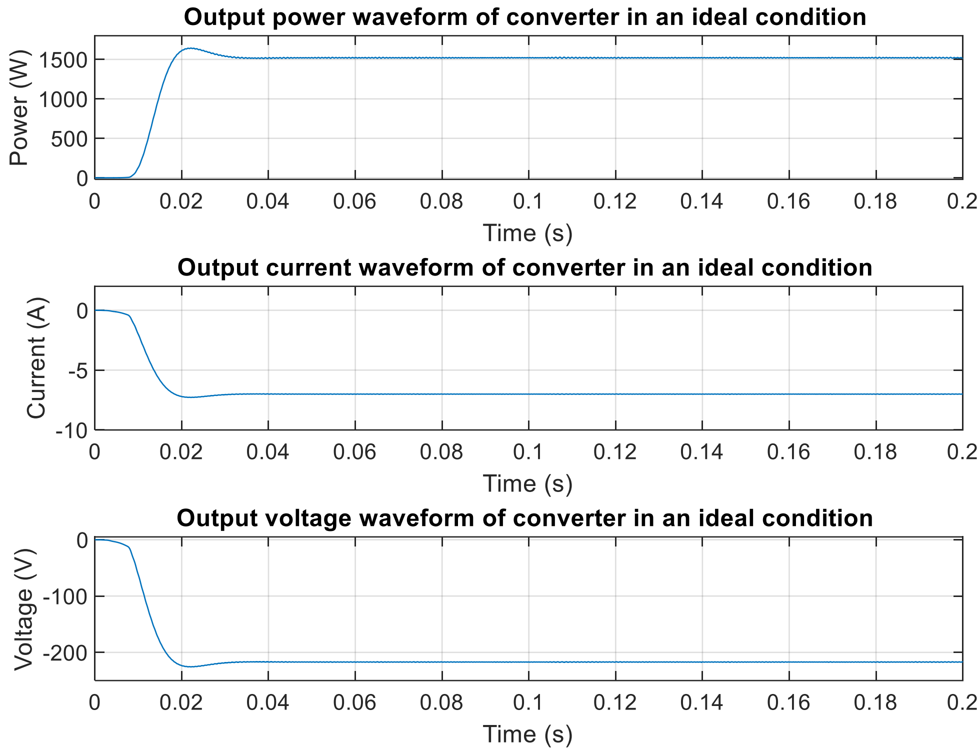


Figure 4.11. Output power energy of converter harvested from five solar panels with full of irradiation G = 1000W/m^2

4.2.2. Behaviour of the multilevel solar converter structure under partial shading irradiance condition

In contrast to the ideal condition above, this part will predict the behavior of the converter when there is unequal irradiation on panels in the system. The string module is assumed to be exposed as G_1 = 200W/m^2, G_2 = 400W/ m^2, G_3 = 600 W/ m^2, G_4 = 800 W/ m^2, G_5 = 1000 W/ m^2.

The consequence is that each panel produces maximum power for its level shading as it shown on figure 4.12. The maximum power points for different irradiances are mentioned in the table 4.2. For example, if the shading irradiance is 200W/m^2, the modules produce 54.6W. Assuming the V_{MPP} is 29.4V, the current is 54.6/29.4 = 1.85A. The total power produced by the string theoretically is 54.6 + 115.5 + 179 + 244 + 310 = 902.9W. The voltage path needs to be maintained at 225V, the current path to the inverter now is 902.9W/225V = 4A.

For the shaded module, the output voltage will be 54.6W/4 = 13.65V. In this case, the un-shaded modules produce maximum power and work as a boost converter, step up voltage and step-down current. Whereas the shaded module acts as a down converter which decreases the input voltage and increases current. All the data are collected and shown in the table below.

Modules		1	2	3	4	5
Irradiance (W/m²)		200	400	600	800	1000
PV	Current (A)	1.7	3.2	5	6.7	8.4
	Voltage (V)	32	34	35	36	36.5
	Power (W)	54.4	108.8	175	241.2	307
Output Converter	Current (A)	4	4	4	4	4
	Voltage (V)	13.6	27.2	43.75	60.3	76.75

Table 4.2 Data selected from the simulation for five module with different irradiance

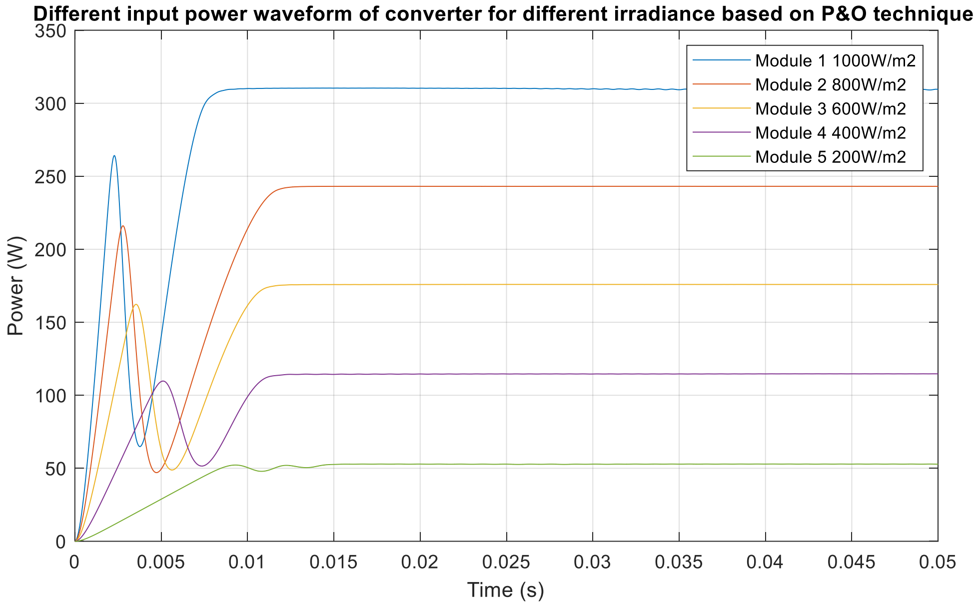


Figure 4.12. Input power energy harvested from five solar module with different irradiation (G_1 = 200W/m², G_2 = 400W/m², G_3 = 600 W/m², G_4 = 800 W/m², G_5 = 1000 W/m²)

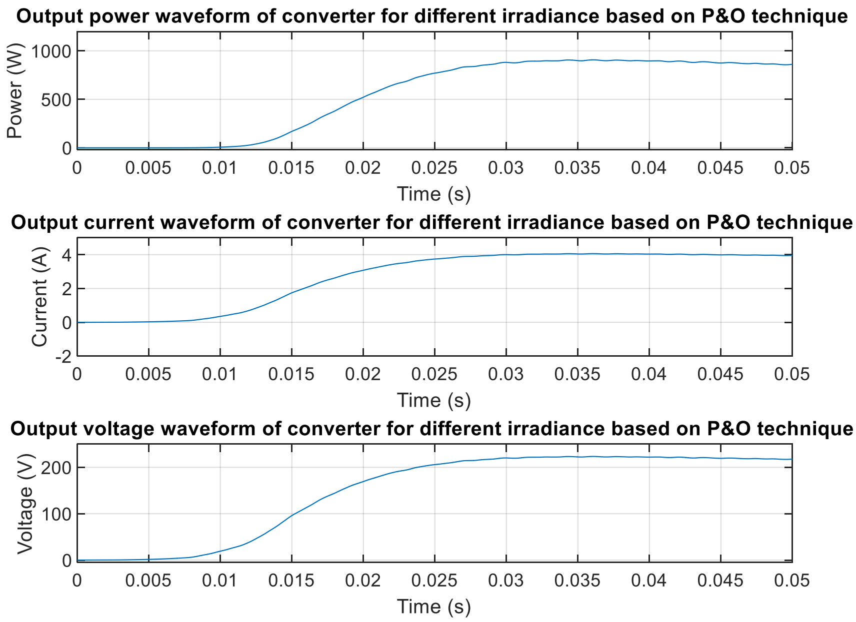


Figure 4.13 Output power energy harvested from five solar panel after the converter (G_1 = 200W/m², G_2 = 400W/m², G_3 = 600 W/m², G_4 = 800 W/m², G_5 = 1000 W/m²)

4.3. Discussion of the results.

Module		1	2	3	4	5	Total
Irradiance (W/m²)		200	400	600	800	1000	3000
$P_{TrueMPP}$ (W)		54.6	115.5	179	244	310	902.9
Output power (W)	Common	-9	-6	170	212	222	589
	Multilevel	54.4	112.8	176	242.2	308	893.4
Efficiency (%)	Common	-16	-5	94	86	71	64
	Multilevel	99	94	98	99	99	99
Recovery energy (W)	In watt	59.1	114	7.8	31	85	304.4
	In percentage	108	104	4.3	12.7	27	34

Table 4.3 Synthesize data of commonly used solar structure and multilvel solar converter structure.

Table 4.3 synthesis the data of commonly used solar converter structure and multilevel solar converter structure under partial shading. The table contains the true maximum power point ($P_{TrueMPP}$) which is collected in table 2.1 for each module with unequal irradiance. The purpose of this table is to consider the output power, efficiency, and recovery energy between the two structures.

It can be seen that the multilevel solar converter has an output power higher than the commonly used solar converter at every shading level. With strong shading, the commonly used solar converter even consumes the power while the multilevel one produces maximum power point at that level.

The multilevel has a high efficiency of 99% for extracting solar energy while the common one low efficiency of around 64%. Similarly, the recovery energy of the multilevel solar converter structure has saved more power than the commonly used solar converter structure.

Besides, the input and output of the converter for this structure have shown over time in several figures of two solar converter configurations. The multilevel solar converter structure has a faster response compared to the commonly used solar converter. Especially in partial shading conditions, the response is faster twice than the common one.

In general, the simulation has proved that multilevel solar converter structure had taken against the commonly used solar converter structure. It saved 34% of efficiency which transfers the energy from photovoltaic solar to the main power in the fastest way.

Conclusion

The thesis proposes two simple structures to analyze and compare the properties of each structure. The conventional solar power converter structure and multilevel cell converter structure are simulated in the MATLAB environment and shown clearly in figure 4.3 and figure 4.10.

The difference between these two structures is that the multilevel structure has its converter with MPPT technique control on each panel and without using a diode. The conventional one has one bypass diode connected parallel with the solar panel and only one converter with MPPT technique for one string system.

For easier comparison, each structure got a similar number of panels for harvesting energy and the same structure of converter. The test was divided into ideal condition and partial shading condition of irradiance. Several considerations for comparison were drawn up.

The selective results simulations are shown in the study. With P&O based on the MPPT technique at each module without bypass diode, the power is achieved almost at maximum level. Because of the series connection, one of the most consideration is the current path to the inverter. Under partial shading conditions, the multilevel cell converter solves the problem and could even greatly enhance up to 33% of total power than the conventional one.

Another aspect of the idea is the location of the MPPT would decide the power and efficiency it could raise from the solar panel and also supply to the inverter. Each solar panel has its characteristic under different conditions. The MPPT technique based on it could track the maximum power point on its characteristic.

The series connection plays an important role in supplying sufficient voltage to the main power grid. In this case, the multilevel cell converter has more advantages due to its structure. Based on the development of power electronics, the efficiency can gain from 90% to 98% which significantly reduces power loss. Each solar panel can boost its maximum voltage to a higher voltage so we do not need many panels to connect in series to get more voltage.

For the convenience of the multilevel cell structure, it could monitor each module directly in partial shading. Furthermore, there will be more flexibility to expanse the modules system in the future. However, it takes more installation and maintenance for this structure so it’s better for small-scale solar power plants.

References

Ahmad, J. (2010). A fractional open circuit voltage based maximum power point tracker for photovoltaic arrays.

Apricus. (n.d.). PV Panels. Retrieved February 19, 2021, from http://www.apricus.com/solar-pv-systems-pv-panels-19.html

Dhass, A. D., Natarajan, E., & Ponnusamy, L. (2012). nfluence of shunt resistance on the performance of solar photovoltaic cell.

Do, T., Burke, P., Baldwin, K., & Nguyen, C. (2020). Underlying drivers and barriers for solar photovoltaics diffusion: The case of Vietnam. *Energy Policy, 144*.

Doubleday, K., Choi, B., Maksimovic, D., Deline, C., & Olalla, C. (2016). Recovery of inter-row shading losses using differential power-processing submodule DC–DC converters.

Elgendy, M. A., & Atkinson, B. Z. (2013). Assessment of the Incremental Conductance Maximum Power Point Tracking Algorithm.

Fatemi, S. M., Shadlu, M. S., & Talebkhah, A. (2019). *Comparison of Three-Point P&O and Hill Climbing.* Iran.

Gatz, S., Dullweber, T., & Brendel, R. (2011). Evaluation of Series Resistance Losses in Screen-Printed Solar Cells With Local Rear Contacts.

Infineon. (2015). IR MOSFET - StrongIRFET™.

Infineon Technologies. (2002). How to Select the Right CoolMOSTM and its Power Handling Capability. *How to Select the Right CoolMOSTM and its Power Handling Capability*.

Kaushika, N., & Rai., A. K. (2007). An investigation of mismatch losses in solar photovoltaic cell networks.

Madsen, D. N., & Hansen, J. P. (2019). Outlook of solar energy in Europe based on economic growth characteristics.

Mankins, J. (2014). *The case for space solar power.* Virginia: Virginia Edition Publishing.

NREL. (n.d.). Champion Photovoltaic Module Efficiency Chart. Retrieved February 17, 2021, from https://www.nrel.gov/pv/module-efficiency.html

R.Ramaprabha, & Dr.B.L.Mathur. (2009). Impact of Partial Shading on Solar PV Module Containing Series Connected Cells . *International Journal of Recent Trends in Engineering*.

Sunceco. (n.d.). *300 W – 320 W Poly-crystalline Solar Module*.

Svarc, J. (2020, March 20). Solar Panel Construction. Retrieved February 19, 2021, from https://www.cleanenergyreviews.info/blog/solar-panel-components-construction

Winston, D. P., Kumar, B. P., Christabel, S. C., Chamkha, A. J., & Ravishankar Sathyamurthy. (2018). Maximum power extraction in solar renewable power system - a bypass diode scanning approach.